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The Cover: A rectifier substation in one of the plants built to supply the prodigious amounts of aluminum required for war. The units are of the ignitron type, arranged in groups of 12 to supply 5,000 cathode amperes.

Photo courtesy General Electric Company

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HIGH LIGHTS . .

Circuit-Breaker Performance. Recent tests on the response of high-voltage circuit breakers to both single- and double-frequency transient recovery voltages having natural frequencies up to 200,000 cycles per second showed that there were similarities in the performances of different types of breakers, that the difficulty of interruption did not increase indefinitely with increasing natural frequency, and that the maximum arcing time at a given voltage and current was obtainable in a high-power circuit-breaker testing laboratory (*Transactions pages 804–13*). In view of the present increase in the use of capacitors in banks up to 10,000 kva and the necessity of applying adequate power circuit breakers to the task of switching these large banks, an analysis of the duty on the circuit breaker and its effect on the system during switching is presented, along with test results on full-scale and miniature capacitor bank (*Transactions pages 821–31*).

Chicago Subway. First unit of the $64,000,000 Chicago subway now being completed, the five-mile State Street subway route, is expected to be in operation early in 1943. Centralized supervisory control of the all-relay type includes most modern accessories, such as an illuminated diagram board and remote-control dispatching equipment. Train movements will be controlled throughout by a modern signal and electropneumatic interlocking system with automatic stops (*Transactions pages 780–7*).

Reversed-Refrigeration Heating. Two plants now operating successfully indicate that it is possible and practical in some locations to obtain heat by a process of reversed refrigeration in which the hot condenser-cooling water of the refrigeration plant, usually discarded, is employed. The reversed-refrigeration method is described in this issue and operation data on two large installations presented (*pages 556–60*).

Carrier on the TVA System. Carrier-pilot relaying and carrier-telephone communication have been installed to meet the difficult requirements of relaying and intra-system communication on the extensive Tennessee Valley Authority system. Reasons for the selection of these methods and analysis of their application, the difficulties encountered, and their over-all performance are presented (*pages 561–72*).

Transient Recovery Voltages. Transient recovery-voltage characteristics are assuming a more important place in the design and operation of circuit breakers with the growth and increasing capacity of power systems. A method for determining these characteristics is presented in a paper in this issue, which also includes capacitance data for the more important circuit elements (*Transactions pages 771–9*).

Rectifiers. Mercury-arc rectifiers are being used increasingly to supply power to d-c utilization systems in the United States. High-speed anode switching appears to be the most satisfactory type of arc-back protection in the application of these units. Test data are presented on the performance of a multiple high-speed air circuit breaker for this use (*Transactions pages 788–96*).

Young Engineers and the War. An engineer in a letter to the editor clears up some uncertainties regarding the allocation of young engineers in industry, in the Army, and the Navy stating that highly skilled and trained men should not be inducted indiscriminately into the armed forces when it appears that they are more valuable to the war effort as members of the industrial army (*pages 585–6*).

Nomination of National Officers. Nomination of AIEE national officers to be elected in 1943 will be made at the national technical meeting, New York, N. Y., January 25–29, 1943, by the national nominating committee. Institute members are invited by the committee to contribute suggestions for nominees. Independent nominations also may be made (*page 573*).

Expense for Service Restoration. An analysis is presented of the effect of different types of overcurrent protective equipment and combinations thereof, on the man-hours and the automotive miles required to locate faults, to make necessary repairs, and to restore service (*Transactions pages 813–21*).

Motor Noise. Stator and rotor harmonics are primarily responsible for noise in induction motors. A paper in this issue discusses the resistance and reactance of the rotor with regard to the different harmonics, and presents methods of determining the magnitude of the forces that produce the noise (*Transactions pages 797–803*).

Committee Chairmen. Recently appointed chairmen of AIEE general and technical committees, some of whom already have been introduced (*Oct. EE. '42, pp. 528–30*), are presented to the membership through biographical sketches appearing in the "Personal" section (*pages 574–8*).

Vacuum-Tube Oscillators. Vacuum-tube oscillators have made possible many new applications in the fields of surface hardening, brazing, and soldering. Their advantages are extreme localization of the heat, speed, cleanliness, and uniformity of results (*Transactions pages 831–4*).

Joseph Henry—Pioneer. Henry's little-known experiments on "induction at a distance" were really the forerunner of radio, the AIEE president pointed out at a recent celebration in Philadelphia, Pa., of the 100th anniversary of Henry's experiments (*pages 550–3*).

AIEE Members Honored. The John Fritz Medal and the Hoover Medal were awarded recently to two members of the Institute, the former to Willis R. Whitney (A '01) and the latter to Gerard Swope (F '22) (*page 582*).

Impregnated-Paper Insulation. A report on the AIEE–Engineering Foundation research project on the stability of impregnated-paper insulation briefly reviews the results obtained since the inception of the project in 1936 (*pages 554–5*).

Wartime Efficiency. A Canadian engineer surveys Canada's progress in the prosecution of the war and prescribes a nationwide efficiency program to accelerate it (*pages 547–50*).

Engineering Man Power. The Engineers' Council for Professional Development recently adopted a resolution regarding the distribution of engineering man power for war (*pages 583–4*).

Coming Soon. Among the special articles and technical papers now in preparation for early publication in *Electrical Engineering* are: a review of American and European switchgear practice by J. B. MacNeill (M '36); a discussion of the use of organic plastics as electrical insulating materials by John Delmonte (A '36); an article on lightning protection of hazardous structures by G. D. McCann (A '38); a study of a-c wave form and wave-form standards by Frederick Bedell (F '26); an analysis of characteristics of the three-winding transformer ring-bus system by G. W. Bills (A '38) and C. A. MacArthur; a presentation of formulas for inverse functions of complex quantities by H. B. Dwight (F '26); a description of the use of a d-c board for a-c network analysis by W. E. Enns (A '37); a discussion of the design, manufacture, and installation of a 120-kv oil-filled cable system in Canada by D. M. Farnham (M '42) and O. W. Titus (M '36); a survey of air-blast circuit-breaker installations in Canada by H. W. Haberl (A '28) and R. A. Moore; a description of high-voltage air-blast circuit breakers by A. K. Leuthold (M '42); a discussion of current-transformer differential protection by P. W. Shill (M '42); and an analysis of a single-pole service-restoring device by E. E. Tugby (A '42).

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Wartime National Efficiency

G. A. GAHERTY

Recognizing that war causes a dislocation in a nation's economy which in turn tends to lower its efficiency, a Canadian cites the necessity for expediting war production in Canada and suggests a national-efficiency program applicable to any nation at war. He declares that to achieve victory there must be a judicious allocation of men and materials for the maximum output of the implements of war and for the curtailed output of essential civilian goods; that there must be a rigorous practice of conservation on the part of individuals, business, and government; and that there must be a forfeiture of personal convenience where the national welfare is concerned.

CANADA now has been at war for three years and in that time has advanced far along the road to total war. It is timely to consider the war experiences of Canada, and the conclusions that can be drawn from them, since the war program of the United States, as it unfolds, is likely to follow much the same pattern.

At the very outset Canada became a major and rapidly increasing source of supply for Britain of aluminum, copper, zinc, foodstuffs, and automotive equipment. The financing of these purchases, a billion dollars of which were assumed by the Canadian Government, was a heavy strain on Canadian economy, but thanks to the foresight of the Canadian Department of Finance, stringent control of foreign exchange was imposed and enforced from the outbreak of war. While this brought the war home to Canadians who wanted American funds, it enabled Canada to finance the British requirements and also to meet her own financial obligations to the United States.

With the co-operation of industry, prices on war goods in Canada were for a time held down to prewar levels, but the industrial activity resulted in so much more money in the hands of wage earners that prices soon began to rise at an alarming rate. Sensing the danger, the Canadian Government with commendable promptness stabilized wages more than a year ago on a cost-of-living basis and established maximum prices for goods and services. These "ceilings" have since been maintained with considerable success, notwithstanding the efforts of certain labor and agricultural pressure groups.

ALLOCATE MEN AS WELL AS MATERIALS

Income and other taxes have been raised until those whose income is dependent upon the profits of corporations are taxed even more heavily than in Britain. The excess profits tax has been increased to 100 per cent, of which 20 per cent represents compulsory savings refundable after the war. Compulsory saving has been instituted for those on salaries and wages, and installment buying has been curbed. Gasoline, sugar, coffee, and tea have been rationed throughout Canada. The civilian use of rubber, copper, aluminum, and steel has been cut almost to nothing and even their military use is drastically restricted. The manufacture of many articles has been prohibited. Notwithstanding these measures, the shortage of labor has become so acute that vital war industries such as shipbuilding are now working at reduced capacity because of inability to get men. Selective service, which the Government has just introduced, is designed to make more men available for war work, but there is a definite limit to the Canadian manpower supply and the war effort can be further stepped up only through the more effective utilization of resources in man power and materials, in other words, by wartime national efficiency.

With all due respect for the splendid progress to date, this is no time for complacency. We are facing a crafty and unscrupulous enemy. He has cut us off from our main sources of three vital war materials: tin, tungsten, and rubber. He is taking a heavy toll of shipping and has played havoc with lines of communication, notably his severing of the Mediterranean route to Suez. Resources are being dissipated by the resulting necessity for convoying, for shipping via roundabout routes, for building ships to replace those he is sinking, and for constructing synthetic-rubber plants. His resources, at the same time, are increasing as he puts to work the enslaved peoples of Europe.

Make no mistake of it, victory can be achieved only by the complete mobilization of *all* our resources and their skillful employment in offensive operations; in other words, total war. *We must seek out and destroy the enemy.* It is not the total number of men in the army that counts, but the fire power and the mobility of the armed force with which to strike across the English Channel and in the China Sea. The Navy, Army, Air

Essential substance of an address given September 9, 1942, at a dinner meeting of the AIEE Pacific Coast convention, Vancouver, B. C., Canada.

G. A. Gaherty is president of the Montreal Engineering Company, Ltd., and a member of the Engineering Institute of Canada.

Force, and munitions industry must all be developed in proper balance so that an attack can be made with maximum effect.

MILITARY VERSUS POLITICAL STRATEGY

The great weakness of democracies is that their resources too often are frittered away through the deciding of war policies on grounds of political expediency rather than of military strategy. In Canada, for example, in calling up men for military service, whether they are married or single is the criterion, and single men who are too old are taken in preference to married men better fitted for fighting. In matters of this kind motives of self-interest still dominate, unfortunately. Our problem is to better, by democratic means, what the National Socialists of Germany achieve by enslavement, espionage, and lying propaganda. The stepping-up of Canadian national efficiency for war involves not only the problem of allocating each individual to his proper sphere, but also the problem of recognizing and counteracting the various subversive forces and of building a morale conducive to the *maximum output per individual*.

A major war causes an upheaval in national economy that in itself tends to lower national efficiency. In peacetime we live largely by taking in each other's washing. We exchange goods and services, money serving as a convenient medium whereby transactions can be effected that are fundamentally barter. The real wages for our services are not the money we receive, but what that money will purchase in goods and services. Such goods and services can be made available in wartime only at the expense of war production, and herein lies the main difficulty of a wartime economy. For the *total war* in which we are involved, the very *minimum standard of living* for everyone is indispensable, as is also the *maximum war output per individual*. The problem is how to get everyone working to his utmost with the very minimum of immediate reward.

LIVING STANDARDS VERSUS WAR PRODUCTION

A major war produces a tremendous dislocation of income, and consequently of purchasing power. On the one hand, many businesses such as the automobile business become war casualties; salaried people must work longer hours but for an income that is much reduced by taxation; those who have invested their savings in common stocks, the very foundation of our industrial progress, have their income taxed first in the hands of the corporation, and then again when it reaches the individual. On the other hand, wage earners in most cases are much better off. They are fully employed and they work longer hours often at high overtime rates. Some of them, who ordinarily would be considered unemployable command good wages under the present acute labor shortage. It is not surprising to find them breaking out in a spending rash and buying those things which heretofore they have been unable to buy. Thus we find an increased demand for the very goods the production of which must be curtailed or cut off to wage a successful war. It is this increased demand with a diminished supply of such goods and services that starts the inflationary spiral.

How best to curb the purchasing power of the individual while the war lasts is the question facing us today. Taxation, rationing, and curtailment of production of nonessentials all have their place, but if carried too far promote discontent, and for maximum output it is indispensable that our workers be happy. We must do our utmost to induce the workers to postpone the enjoyment of the fruits of their labor until after the war; in other words, to save. It is of no great importance whether the savings are in war loans, or in bank deposits, or in paying off a mortgage, so long as the money is not spent on services or goods the production of which involves the use of man power or of critical materials. It should be recognized, however, that a modicum of nonessentials, and even of luxuries is indispensable if the worker is to be kept happy, and we should concentrate on those that involve the least use of man power and critical materials.

WHAT IS "ESSENTIAL"?

The individual view as to what is "essential" depends largely on "whose ox is gored." There is the example of a labor deputation, in a Canadian province that prides itself on its patriotism, arguing that a local newsprint mill should not be shut down but that instead "nonessential" industries should be discontinued. Needless to say, the deputation did not elaborate on what industries it considered "nonessential" and why. We in the light-and-power business, until recently at least, have considered electricity to be indispensable. True, it is essential for the mass production of munitions, but for the household it is only a convenience. Further, the use of electric power for the display advertising of goods, the sale of which should be restricted, is a positive detriment to the war effort.

Essentiality is also a question of degree. A 4-page newspaper might be deemed essential, but not so a 40-page one. Wheat and flour are just as essential for our war effort as shells, but we do not need all the 400,000,000 bushels that the Canadian prairie produces. When production facilities exceed essential needs, efficiency generally can be achieved best by maintaining capacity operation in enough plants to produce only the required amount of goods, allowing these plants an adequate supply of labor and materials, and by closing down plants which produce goods in excess of exact needs. This already has been done in several Canadian industries, such as sugar refining.

Essentiality is a word that cannot be qualified. Either a thing is essential or it is not; but one cannot say that one thing is more essential than another, that tanks are more essential than guns. Both are needed

in definite proportions, although one may be needed in advance of the other. Already the Englishman has been forced to recognize this principle and has done away with priorities almost entirely. To obtain the requisite materials, however, a "certificate of essentiality" is required, and by this means nonessentials are cut off and war work is limited to what existing facilities and resources can produce efficiently.

We must always remember that there is a definite limit to what we can produce, and if we attempt to push our production too far we end by actually producing less. The law of supply and demand works as far as labor is concerned, and if the demand exceeds the supply the loafer comes into his own and efficiency drops. It is therefore imperative that we cut our suit according to our cloth and concentrate our attention on the more effective use of our existing resources—men as well as materials.

The curbing of nonessential spending by companies and by governments insofar as it involves the use of man power and of critical materials is just as important as in the case of the individual. Expenditures for extensions and replacements should be avoided wherever possible, and old equipment made to last. Accounting, sales, and other departments should be streamlined to eliminate all unnecessary posts, current maintenance should be deferred to the very limit. For example, a Canadian power company is adopting a bimonthly accounting period. It should be recognized, however, that company policy regarding replacements and maintenance is something that from its very nature is beyond the control of the government and that to secure the full co-operation of the companies, it is indispensable that labor and materials for maintenance and replacements be made available as necessary on a high priority. Otherwise the far-sighted plant manager is likely to stock up with spare parts and keep his plant in a high state of repair for fear of getting caught with a prolonged shutdown because of material or labor shortage.

GOVERNMENTS CAN ECONOMIZE TOO

For years civil government has been absorbing a greater and greater proportion of workers, but we have now reached a point where we must revert to the simpler life of earlier days. Our various government agencies now provide innumerable services ostensibly for the benefit of the public that could be dispensed with until after the war. Every civil servant that can be diverted to war work is just so much clear gain even if his full former salary is continued. Public-utility commissioners judges, and so forth, have the experience needed to administer the various war controls, and already in Canada the services of such men are being used in war jobs.

Throughout the country the construction of public works such as roads is rapidly being tapered off and before long we expect to see it cease altogether, as more and more of our political leaders are realizing that such work is carried out only at the expense of our war effort. A much more difficult problem arises in connection with works having a wartime justification such as housing projects. Here it is a case of relative importance. We must always remember that every house we build is at the expense of our production of guns and tanks, and we must decide which we need more. Obviously it is better to be somewhat overcrowded than to have our country overrun by the enemy. Too much overcrowding however results in discontent among workmen and a lowering of the war output per man. The danger is that local pressure groups will force the building of housing projects, when in the national interest the man power and the materials are more urgently required for other purposes. Such pressure groups usually are led by well-meaning citizens who think they are doing a public service, but their activities should be recognized in their true light as one of the most effective forms of sabotage.

In such questions the short-term view must be taken. It is the current expenditure of material and man power that counts. Whether it be a naval barracks, a munitions factory, or a housing project, the use of temporary instead of permanent construction is fully justified wherever any saving can be made in man power or critical materials, as this will mean that many more ships and guns can be turned out currently, and they are needed *now*.

Our armed forces constitute the chief drain on our total man power and therefore it is the efficiency with which they are employed that is the main factor in our war effort. The total *number* of men in the army means nothing. It is the number that can *strike* in a theater of war and their fire-power that counts. It is not the number of tanks and airplanes, but their fighting qualities that count. Too often in democratic countries sectional pressure leads to forces being immobilized to guard against possible hit-and-run raids and other military diversions. Also, shore establishment in dockyards may be built up, although repair work might be done with less use of man power by shipbuilding contractors. More men may be used to guard munition plants than would be required to restore any damage likely to arise from sabotage if the plants were left unprotected. These are questions that should be dealt with by the General Staff, but it is the duty of every citizen to see that the General Staff in making these decisions is unhampered by the sinister activities of pressure groups.

IF WE ARE TO STOP LOSING THIS WAR—

If we are to stop losing the war, further industries and businesses will have to be shut down. In some instances these necessary changes involve disturbing implications. South Africa, for example, is almost entirely dependent upon the gold-mining industry, but that industry is not essential to the war effort of the United Nations. It is

only by the drastic curtailment of nonessential industries that sufficient labor can be made available to relieve the acute shortage in war industries. The 40-hour week and the various conditions of labor which require the employment of three men where two would do, jurisdictional limitations which prevent a man from handling more than one job—these, too, are contrary to the national interest in wartime when all must produce the utmost.

We in the power business have had to slip into reverse. It is no easy matter to overcome the training of years and start saving electricity so that it will be available in sufficient quantity for essential war industries. That is to say, we must forego sales that are our bread and butter to take on business that is financially unattractive. At least one power company in Canada is already replacing copper conductors with iron wire on lightly loaded primary circuits so as to make more of this scarce metal available for war purposes.

Beware of the individual who looks upon the war as a golden opportunity to introduce his pet social theory, such as prohibition which was foisted on the country in the last war. Thumbs down on those who, by spreading racial, sectional, religious, or class prejudice, would divide and rule.

Promote, particularly among those in the lower income brackets, a better understanding of the reasons for war hardships. Provide the necessary incentive so all will work to the utmost. Save both as individuals and in one's official capacity so that man power and material can be conserved for war work. This is the way to step up our wartime national efficiency.

Joseph Henry—*Pioneer in Electrical Science*

H. S. OSBORNE
PRESIDENT AIEE

Henry's little-known experiments on what he called "induction at a distance," conducted 100 years ago, were really the forerunner of radio. Since this present war has been labeled a "radio war" because of the great importance in military and naval activities of the transmission of electromagnetic waves, it is particularly appropriate to take this radio anniversary as the occasion for honoring this great pioneer in electrical science.

ON October 21, 1842 in the hall of the American Philosophical Society, which is still standing on South 5th Street here in Philadelphia, Joseph Henry "communicated orally," (and I quote from the records of the American Philosophical Society) "an extension of the experiments, which he had previously brought before the Society, on electrodynamic induction. He had succeeded in magnetizing needles by the secondary current in a wire more than 220 feet distant from the wire through which the primary current was passing, excited by a single spark from an electrical machine."

The earlier experiments reported in June of the same year were recorded as follows in the minutes of the American Philosophical Society:

"... a single spark ... thrown on the end of a circuit of wire in an upper room, produced an induction sufficiently powerful to magnetize needles in a parallel circuit of wire placed in the cellar beneath, at a perpendicular distance of 30 feet with two floors and ceilings ... intervening."

In the later experiments reported in October, a wire for transmitting had been stretched across the campus of Princeton University in front of Nassau Hall, grounded at one end by a plate buried in the ground. A second wire for receiving was erected in the back campus. A high-frequency oscillatory current was produced in the transmitting wire by discharging into it a battery of Leyden jars. A small steel needle was placed in the center of a spiral of wire, which formed a part of the receiving circuit. This needle was magnetized when the discharge took place in the transmitting circuit.

These little-known pioneer experiments are believed to be the first recorded experiments on radio transmission. They were carried out 45 years before the experiments of Hertz which established the existence of electrical radiation and determined many of its electrical properties. They were more than 50 years earlier than the pioneer work of Marconi in which this phenomenon was put to practical application—the first radio telegraph system.

This centennial anniversary of these astonishing early experiments may be called a radio anniversary. While Henry's contributions to the development of science and of its application cover a wide range, it seems particu-

Essential substance of an address presented at a meeting of the AIEE Philadelphia Section, Philadelphia, Pa., October 12, 1942.

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larly appropriate to take this radio anniversary as the occasion for pausing in the hurly-burly of the day's preoccupations to do honor to this great pioneer in electrical science. The knowledge and the application of radio are now being pressed forward with feverish activity, probably more intensively than any other branch of electrical science and its applications. Someone has labeled the present war "a radio war" because of the great importance in military and naval activities of the transmission of electromagnetic waves, of which Henry's experiments, just 100 years ago, were the forerunner.

It seems improbable that these experiments of themselves are one of Henry's great contributions to radio. They represent a case of Henry being so far ahead of the procession that it is doubtful how much direct effect these experiments had on the subsequent development of the electrical arts. Henry himself might well have advanced them to the point where they would have resulted in direct effect on the electrical arts, had he not, shortly after these experiments were made, dropped his individual research in order to organize and direct the newly formed Smithsonian Institution. For in Henry's remarkable career during the previous 15 years he had shown not only a capacity for exact research but a knack for practical design. While he was not interested in the commercial application of his scientific discoveries, this bent for the practical made his discoveries peculiarly effective in the subsequent development of the electrical arts and sciences.

Joseph Henry, a pioneer in electricity; from a bust sculptured by John Flanagan

Let me outline briefly the discoveries and accomplishments of Henry in the field of electricity which appear to have most important application in the radio art of today. First, as a background for the consideration of Henry's discoveries, I should mention two important discoveries which had recently been made in Europe. In 1820, Oersted in Denmark, had discovered that an electric current exerts a force upon a magnetized needle. This remarkable discovery led Sturgeon in England, and others, to construct electromagnets consisting of a spiral of bare wire wound upon an insulated iron core.

In 1827, Ohm's famous law was published in full in Berlin. This law, however, was little known or accepted even in Europe for a decade, a fact which well illustrates the poor state of communications at that time.

In 1829 Henry devised great improvements in the construction of electromagnets which made them much more powerful tools for investigation. Instead of winding a single spiral of bare wire on an insulated magnetic core as heretofore, Henry conceived the idea of insulating the wire and winding many closely wound layers on the core. This, of course, greatly increased the power of the electromagnet and transformed it from a scientific toy into a practical device for investigation and for use.

This improvement also laid the basis for applying to electromagnets and to the circuits in which they were used certain fundamental principles of design. Experimenting with these new magnets in 1830, Henry determined experimentally the correct proportioning between the winding of the magnet and the connection of the battery for maximum magnetic effect, showing that the intensity (or high-impedance) magnet and battery were suitable for operating over line wires of considerable resistance, while the quantity (or low-impedance) magnet and battery were suitable for local circuits. This result, as you know, could be derived mathematically from Ohm's law and from the relation between ampere turns and magnetism of an electromagnet. However, Henry derived this relation experimentally before he had any knowledge of Ohm's law. It is the first recognition of the necessity for properly proportioning the impedance of different parts of an electric circuit, a general principle of design which is fundamental in the design of radio circuits and which has, of course, very wide application in other fields.

These advances led Henry to set up in 1831 the first telegraph circuit using an electromagnet as a receiving device. The line ran between his house and his laboratory, and it is said that his wife used it to call the deeply engrossed professor home to meals. He supplemented this in 1835 by the addition of the first electromagnetic relay by means of which the relatively weak current received over the line was used to control the flow of a larger current in a local circuit.

In 1831 and 1832, working independently, Faraday in England and Henry in this country both discovered mutual induction and self-induction. Based upon dates

of publication, the discovery of mutual induction is credited to Faraday and that of self-induction to Henry. Henry's discovery of self-induction is probably the most widely known of his accomplishments and has been immortalized by the adoption by the International Electrotechnical Commission of the term "henry" for the unit of inductance.

Henry's work on self-inductance led him in 1835 to devise noninductive windings designed to reduce to a minimum the effect of self-induction. These were built by doubling the wire in the middle and then coiling the doubled wire—a principle of design which survives to this day.

His work on mutual induction led Henry in 1838 to discover that, by the proper proportioning of a primary and a secondary coil the voltage could be stepped up or down. He thus established the fundamental basis for the development of transformers. He also showed the variation in the current induced in the secondary circuit as the separation between the primary and secondary coils is varied. This is the principle of the variometer widely used in radio.

In 1842 Henry made a contribution of great import by confirming the oscillatory nature of the discharge of the Leyden jar. In 1827 Felix Savary of France, investigating the magnetization of small steel needles by the discharge of a Leyden jar, found to his surprise that the polarity of the magnetized needle varied with its distance from the conductor carrying the discharge. Up to that time it had been assumed that such a discharge was continuous in one direction. Savary raised the question whether these anomalous results could not best be explained by assuming that the discharge was not simply a single flow in one direction but instead was a series of rapidly succeeding discharges in opposite directions. In 1842 Henry reported the results of experiments which confirmed Savary's hypothesis and made a clear and authoritative statement of the phenomenon as follows:

"The discharge, whatever be its nature, is not correctly represented (employing for simplicity the theory of Franklin) by the single transfer of an imponderable fluid from one side of the jar to the other; the phenomena require us to admit the existence of a principal discharge in one direction, and then several reflex actions backward and forward, each more feeble than the preceding, until the equilibrium is obtained. All the facts are shown to be in accordance with this hypothesis, and a ready explanation is afforded by it of a number of phenomena which are to be found in the older works on electricity, but which have until this time remained unexplained."

The establishment in this way of the existence of high-frequency oscillations was, of course, a great step forward in the electrical arts. It was mathematically explained 13 years later by Lord Kelvin and was the basis of the work of Hertz on electrical radiation, 40 years later.

Henry's work on the oscillatory character of the discharge of the Leyden jar directly preceded his experiments on what he called "induction at a distance," which are the occasion of this radio centenary. In these experiments he used the discharge of the Leyden jar. The knowledge that the discharges were oscillatory led Henry to surmise that these electrical phenomena of induction at a distance were of the same nature as the transmission of light. This striking flash of genius seems to have been another case of Henry being way ahead of the procession and deserves our further consideration.

In 1842 the "elastic-solid" theory of light was well established, having triumphed over its rival, the corpuscular theory. In accordance with the elastic-solid theory, the transmission of light consisted of a vibration in an elastic solid of most remarkable properties. The theory became established as a result of the work of Fresnel about 25 years earlier and held sway for many years.

It is true that Faraday in order to visualize the mechanism of the electrical phenomena which he was observing, had conceived the idea of tubes of force representing electrical strains in a surrounding medium. However, this medium had no relation in the mind of scientists to the so-called luminiferous ether, the medium by which light was transmitted.

It was not until 1864 that Maxwell, developing his electromagnetic theory, showed that the propagation of light could be considered as an electromagnetic phenomenon. This was confirmed in 1887 by the brilliant experiments of Hertz which showed that light waves and waves generated electrically are of the same nature.

This background makes thoroughly astonishing the following remark of Henry in reporting his experiments 100 years ago:

". . . when it is considered that the magnetism of the needle is the result of the difference of two actions, it may be further inferred that the diffusion of motion in this case is almost comparable with that of a spark from a flint and steel in the case of light."

This view was even more clearly expressed to Henry's students at Princeton at the time, in his lectures on natural philosophy. Here is the way it is recorded in the contemporary notes of one of the students:

"Hence the conclusion that every spark of electricity in motion exerts these inductive effects at distances indefinitely great (effects *apparent* at distances of half a mile and more); and another ground for the supposition that electricity pervades all space. Each spark sent from the Electrical machine in the College Hall sensibly affects the surrounding electricity through the whole village. A fact no more improbable than that light from a candle (probably merely another kind of wave vibration of the same medium) should produce a sensible effect on the eye at the same distance."

While Henry thus clearly expressed his opinion we would wrong him if we were to assume that this was his set conviction. He was too great a thinker to be dogmatic in such a matter without data to prove that his postulate was correct. He showed the greatness of his nature by being accurate in his description of observed fact but tentative rather than cocksure in his deductions. His views on this point are illustrated by the following comment which he wrote a few years later:

"Man, with his finite faculties, cannot hope in this life to arrive at a knowledge of absolute truth; and were the true theory of the

universe, or in other words, the precise mode in which Divine Wisdom operates in producing the phenomena of the material world, revealed to him, his mind would be unfitted for its reception; it would be too simple in its expression and too general in its application, to be understood and applied by intellects like ours."

To my mind, pausing to honor this great man is not merely a graceful gesture toward the past but also has a real significance in connection with the problems of today. Joseph Henry's career is at any time an inspiration. Son of a day laborer, largely self-educated, he was located in a frontier country which was far from the main stream of scientific thought in Europe and with most inadequate means of communication. But, working incessantly and armed with plain heroic magnitude of mind, he became a great leader of science, not only of this country, but of the world.

He had to a high degree the qualities of a great pioneer of science—qualities necessary for progress at any time in the world's history—curiosity and industry which enabled him to discover new phenomena, accuracy in the observation and correlation of fact, the imagination to see the significance of new facts, even when that meant departing from established paths of thought, and the wisdom to be tentative in his general conclusions.

Perhaps such qualities were never more needed than today. Like Henry we are working in a time of rapid change, when there is great need for the pioneer spirit. Today the changes are perhaps more rapid and on a broader front than ever before. Today we are faced with rapid changes, not only in the field of physical sciences, but in that very broad and difficult field called the social sciences. And in saying this, I have in mind both the war, with its urgent problems, and the postwar period, which will bring new problems just as important and difficult.

I believe, as we measure our wisdom and our strength against the problems and events of these days, that we can be helped by the inspiration of Joseph Henry's life and accomplishments.

General Electric Company photo

Steel parts vital in the production of war goods are first heat-treated in the rotary-hearth electric furnace, the large cylinder in the background, then in the vertical cylindrical air-draw electric furnaces in the foreground

Stability of Impregnated-Paper Insulation

J. B. WHITEHEAD
FELLOW AIEE

A SUMMARY of the principal problems studied in the AIEE–Engineering Foundation research project on the stability of impregnated-paper insulation and results of laboratory investigations are outlined in this report. More detailed accounts of specific phases of the work covered in this project already have been published in AIEE *Transactions*.[1–4]

PAPER DENSITY

Laboratory studies in accelerated life tests of the influence of the density of the paper on the breakdown strength of impregnated-paper insulation have been conducted. The studies were in two series, one using a heavier oil as employed in solid-type cables, and the other using a thin oil as employed in oil-filled cables. The same four grades of paper of different values of density were used in both series.

The results in both cases showed a marked decrease of dielectric strength with increasing paper density, the type of variation being much the same for each oil. However, dielectric strength and life for the series using the thin oil are substantially higher than for that using the heavier oil.

Raising the viscosity of the thin oil and lowering the viscosity of the heavier oil so that both have the same viscosity during impregnation have little effect on the breakdown strength at standard test temperature of 40 degrees centigrade. Specimens impregnated with the heavy oil show no change in behavior. Increasing the viscosity of the thin oil results in a slightly lower dielectric strength. This may be accounted for, however, by the low impregnating temperature, 40 degrees centigrade. When the two oils have the same viscosity at impregnation, the values of power factor and of oil content at 40 degrees are approximately the same.

The explanation of the decrease of dielectric strength and increasing paper density is to be found in the increased dielectric constant of a denser paper. This increase in dielectric constant throws a greater proportion of the total stress on the oil channels and their critical breakdown stress is reached at a lower over-all voltage.

At first, some engineers were loath to accept this evidence that the dielectric strength of impregnated paper decreases with increasing paper density. It is stated that in manufacture, cables containing high-density paper give a higher dielectric strength than those using paper of lower density. While there are comparatively few published data of the results observed on cable, it is clear that the relationship between paper density and dielectric strength found in this research differs radically from the relationship reported for finished cable. In the case of impulse test on cables, a different mechanism of failure may readily explain the difference. In the case of solid-type cables on which tests of longer duration have been reported the values of *specific* dielectric strength for all types of paper are considerably lower than in this research; this well may suggest a different mechanism of failure even for tests of duration comparable to those in this research. Some things which have been suggested as possibly bearing on a difference in mechanism are: that cables are made with stranded conductors as compared with the smooth conductors in this research; that cables must be capable of withstanding bending, and are bent; and that solid-type cables cannot remain completely filled with oil due to expansion and contraction of the impregnant. However, until more complete information is available concerning the cable tests, it will be difficult to assign a definite cause for the apparent discrepancy. In view of the conflict described, it is obviously desirable that the influence of the density of the paper be studied further.

Results obtained in the AIEE–Engineering Foundation research project on the stability of impregnated-paper insulation, since its inception in 1936, are reported briefly. Some unexpected properties of impregnated-paper insulation have been discovered and findings pertaining to paper density, high-stress internal ionization as the origin of failure, and impregnation temperature versus dielectric strength and life indicate that further research in these fields is desirable.

INFLUENCE OF PAPER THICKNESS

A pronounced decrease of dielectric strength with increasing paper thickness has been found and described in a published paper.[2] This result may be attributed to the well-known fact that the breakdown stress of thin oil films decreases with increasing thickness. Further discussion in the published paper analyzes the results and indicates that variations in the value of the critical stress in the oil channels are due to space-charge accumulations at the interfaces between paper tapes and oil channels.

The results of research on paper thickness confirm

Essential substance of a report prepared by Doctor Whitehead and endorsed by the advisory committee of the AIEE–Engineering Foundation research project on the stability of impregnated-paper insulation. This research has been supervised by the following subcommittee of the AIEE committee on research: H. H. Race, chairman, W. A. DelMar, H. Halperin, E. R. Thomas, R. W. Atkinson.

J. B. Whitehead is director of the school of engineering, Johns Hopkins University, Baltimore, Md.; he has conducted the work on the AIEE–Engineering Foundation insulation research project since its inception.

the general conclusions of all these studies that failure begins in an oil channel, and that space-charge accumulations in the oil channels have an influence on the critical or breakdown stress in the channels. The results here are very definite and no special need for further study is indicated.

INFLUENCE OF WIDTH OF OIL CHANNEL

The dielectric strength of impregnated-paper insulation assembled cable-fashion decreases with increasing oil-channel width between successive convolutions of tape, up to a channel width of one-eighth inch and is constant thereafter. Using the thin oil the decrease is about 9 per cent, using the heavier oil, about $6^1/_2$ per cent, as the channel width increases from zero to one-eighth inch.

The increase of dielectric strength with decreasing channel width is probably accounted for by the increasing limitation in the volume of space-charge accumulation. The results in this study again show the higher dielectric strength and longer life of specimens impregnated with the thin oil, confirming the results in the studies of the influence of the density of the paper. In view of the definite character of the results, there seems to be no special need for further studies of this question.

INTERNAL GASEOUS IONIZATION

The basis of the method for detecting the beginning of internal gaseous ionization has been described in a published paper.[3] The method, however, as adapted to the present work, has been modified substantially. It now consists of a rearrangement of the Schering bridge so that a balance is obtained for the principal range of frequencies found in a gaseous discharge in impregnated paper, and at the same time a filtering out of the 60-cycle component in the balance arm. Recent work has included the incorporation into the experimental setup of a continuous recording instrument, which indicates the beginning of internal ionization and measures the subsequent increase of volume or magnitude of ionization. This method has been applied to the study of the behavior of impregnated-paper specimens as used in this project and has already shown that it is possible to interrupt a test on a specimen when failure has begun, but has not advanced through the wall of the insulation more than two or three layers of paper. Not only is it possible thus to locate the initial failure, but also, in other specimens, the rapidity of its advance, and the point at which it swings over into an unstable thermal failure. The studies employing this method are still in the early stages and have given very great promise.

The partial failures in the use of this method and their subsequent dissection and study have confirmed other indications that failures in impregnated paper usually begin in the oil channels. They also have given evidence of causes of power-factor increase and the rate of increase of loss and approach to failure. This method has given greatest promise for further information as to failure in impregnated-paper insulation and is strongly recommended as a promising field for further study.

OPEN VERSUS CLOSED SPECIMENS

The studies on open versus closed specimens are short-time low-temperature studies and have never given any evidence of oxidation or other type of disturbing influence attributable to the open bath in which the specimens are tested.

Comparative tests on open and closed specimens (nine each) resulted in no appreciable differences in dielectric strength or life. The behavior of both closed and open specimens in regard to power factor was similar to data on closed specimens furnished by Doctor H. H. Race, although in the AIEE–Engineering Foundation research the power-factor values are substantially lower, probably because of the difference in temperature.

Power factor–voltage curves in these studies up to 400 volts per mil were almost invariably flat after tests up to and above 100 hours, and with stresses, up to 800 volts per mil. We also have found no power-factor changes in specimens which have remained in the open bath for periods of several weeks.

Tests reported in the paper, "The Life of Impregnated-Paper Insulation,"[5] show flat power factor–time curves for certain oils (Figures 3 and 4) up to 100 hours at 40 degrees, the stress increasing progressively up to and beyond 800 volts per mil.

In view of these and other allied results, it has been assumed that for the relatively low temperature and short time of these tests, the results are not influenced by the open character of the test bath, because the mechanism of failure is predominantly ionization and not chemical deterioration.

Recently, however, there has been some renewed discussion of possible limitations of accuracy of open versus closed test baths, if such tests are conducted at elevated temperature or for more than a few hours. It is certain that the limits of temperature and time in which open baths may be considered as reliable are not known. The relative simplicity of the open-bath method as compared with the closed-bath method undoubtedly gives it certain advantages. It would appear, therefore, that a comparative study of open and closed baths with special reference to the limitations of the former offers promise of useful results.

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Heating by Reversed Refrigeration

REGIS D. HEITCHUE

GIVEN a source of heat which results in a reasonable coefficient of performance, the practicability of a reversed-refrigeration plant will depend upon the cost of electricity relative to coal, gas, or oil, and the initial cost, which in turn will depend upon the ratio of heating to cooling loads. Obviously a detailed survey by a competent air-conditioning engineer would be required to determine whether or not a contemplated installation meets the technical requirements.

Because of the growing popularity of refrigeration equipment for both comfort and process cooling, it reasonably can be expected that the use of reversed refrigeration for heating will increase when it becomes possible to resume the manufacture of the required equipment. In industrial plants requiring refrigeration throughout the year, the relatively hot condenser-cooling water now being wasted might be used to good advantage.

The elements of reversed refrigeration, a method by which heating may be accomplished, are to be found in all refrigerating and air-conditioning systems. In reversed refrigeration the heat derived from the motor and the compressor and from the substance cooled —air or water—is utilized. The method is particularly applicable in industrial plants requiring refrigeration throughout the year, where the relatively hot condenser-cooling water now being wasted might be salvaged for heating purposes. Two industrial reversed-refrigeration plants now in successful operation are described here.

WHAT REVERSED REFRIGERATION IS

One need look no further than one's own kitchen to see the workings of reversed refrigeration. The electric refrigerator has all the elements of this fascinating heating scheme. Suppose the ice trays are filled with cold tap water. Soon this water becomes ice. In the process, the kitchen is heated by an amount equal to the electric energy used by the motor plus the amount of heat taken from the tap water in the trays.

Every refrigerator, air conditioner, or reversed-refrigeration heating system works exactly this same way; in fact the name reversed refrigeration is a misnomer. Heat is extracted from air or water, is combined with the heat developed by the motor and compressor, and added to other air or water. If the cooled air or water is sent to the living or working areas, the conventional air-conditioning system is the result. If, instead, the heated water or air is circulated, a reversed-cycle refrigeration plant is the result. The heat comes from two sources: the electric energy converted to heat by the motor and compressor, paid for as kilowatt-hours; and the substance cooled. It is because this second quantity of heat can be taken from the free air or from low-cost water that the system has the appearance of giving more than is paid for. Heat is simply extracted from an additional source, which, although of lower temperature than the room being heated, still contains a large quantity of heat that can be made available.

Essential substance of a paper presented at a meeting of the AIEE Springfield (Mass.) Section, September 8, 1941; subsequently expanded to include operating-results data.

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TECHNICAL REQUIREMENTS OF A REVERSED-REFRIGERATION PLANT

Source of Heat. Essential to the operation of a reversed-refrigeration heating plant is a suitable source of heat. Not only must the heat source be available in ample quantity, but it must also exceed certain minimum temperature limits, if the gain in heat is to be worth-while.

There are two natural sources of heat: outdoor air and water. In cool climates where freezing temperatures are often encountered, water is the only satisfactory source of heat. In the case of the household refrigerator, the tap water, plus the heat removed from the food is the source. In a large plant requiring considerable heat, the cost of using city water would probably be too great or there might be restrictions on its use for such purposes. Also, in the colder climates, the temperature of the city water, rivers, or lakes would, in all probability, for reasons to be pointed out later, be too low. The drilling of private wells, then, appears to be the only way of affording a source of heat in the colder climates. Where well water is not available or it is not feasible to drill wells, the use of the reversed-refrigeration heating plant is obviously not practical.

Where the outdoor temperature seldom falls to freezing, air may be employed as the source of heat. A disadvantage of air as a source of heat however, is that its temperature is lowest when the need for heat is greatest. Since the efficiency of a reversed-refrigeration plant is greatly affected by the temperature of the source, the use of air might necessitate a larger plant than would be required if water were used.

The quantity of heat to be removed from the source would obviously depend upon the size of the intended

installation. The temperature of the heat source, however, has fairly strict economic limits. In the household refrigerator, heat is removed from the water and given up to the room even during the freezing process. While it would be possible to utilize the heat thus liberated, it would not, in most cases, be economically practical. The minimum temperature limits are 45 degrees Fahrenheit for air and 40 degrees for water. Of course, these limits may be modified somewhat, but as will be shown later, the coefficient of performance or efficiency falls off appreciably with a decrease in the temperature of the heat source.

Coefficient of Performance. The efficiency of a refrigerating machine is defined as the coefficient of performance (*COP*), and is simply the ratio of output to input. In a reversed-refrigeration machine, the output is measured at the condenser, and, disregarding losses, is equal to the heat represented by the motor watts plus the heat removed from the source, or the refrigeration effect. The input is the heat equivalent of the motor watts. The expression then for the efficiency is:

$$COP = \frac{\text{heat from electricity} + \text{heat from source}}{\text{heat from electricity}}$$

It was said that the coefficient of performance is greatly affected by the temperature of the heat source. It is also true that the coefficient of performance is very much dependent upon the condensing temperature, which in turn is dependent upon the medium employed to transfer the heat from the refrigerating machine to the building. In the household refrigerator, the room air is circulated over the air-cooled condenser, absorbing heat directly from the refrigerant through the metal of the condenser. Although this method is practical for small installations, it is not for large ones. Instead, water-cooled condensers are employed. The heat from the refrigerant is first transferred to water and then by means of additional heating coils, the heat is transferred from the water to the room air. The lower the temperature of the water, the higher will be the coefficient of performance. Offsetting this advantage, however, is the disadvantage that as the temperature of the water is decreased, the size of the heating coils must be increased, requiring a greater investment in equipment. In practice, it would be necessary to strike a balance between operating cost as determined by the coefficient of performance and amortization and interest charges. The coefficient of performance for an actual machine, a 100-horsepower condensing unit operating at several evaporating and condensing temperatures is shown in Table I.

Table I. Effect of Evaporating and Condensing Temperatures on the Coefficient of Performance

100-Ton Condensing Unit

Evaporating Temperature Deg. F	Condensing Temperature Deg. F	Heat Absorbed at Evaporator (Cooling Effect) British Thermal Units	Motor Watt-Hours Input	Heat Equivalent of Motor Watts British Thermal Units (Column 4 × 3.415)	Heat Rejected at Condenser (Heating Effect) British Thermal Units (Column 3 + Column 5)	COP (Column 6 ÷ Column 5)
50	96	1,430,000	87,000	297,000	1,727,000	5.80
40	96	1,185,000	83,300	285,000	1,470,000	5.15
34	96	1,040,000	80,500	275,000	1,315,000	4.78
50	117	1,290,000	100,000	341,500	1,631,500	4.77
40	117	1,055,000	94,500	323,000	1,378,000	4.26
34	117	920,000	90,400	309,000	1,229,000	3.97

Operating Costs. The installation and operation of a reversed-cycle heating plant is economically practical only when the total cost of operation is equal to or less than the cost of heating by other methods—coal, gas, or oil. The operating cost is made up of the following:

1. Interest on the capital investment.
2. Amortization of capital investment.
3. Maintenance charges.
4. Electricity.

When the refrigeration and air-conditioning equipment is necessary during the summer months to provide cooling, and the heating load is not much greater than the cooling load, the capital investment and interest charges are not of major consideration. It can be argued justly that only the depreciation and maintenance expense should be charged against winter operation. In such cases, the cost of electricity would be the determining factor. If the cost is high compared with coal, gas, or oil, it might be cheaper to install a separate heating plant. On the other hand, if electricity is cheap, the installation of a separate heating plant might not be warranted. If there were a considerable disparity between the heating and cooling loads and if cooling were a summer-time requirement, then winter operation should be charged with only the additional equipment employed and, of course, depreciation charges on the whole plant. If the cost of operation thus computed were less than that of other methods in which interest and amortization charges were also included, the reversed-refrigeration plant would be economically justified.

PRACTICAL APPLICATIONS

The reversed-refrigeration plants chosen for discussion were selected because of their sizes, locations, sources of heat, and methods of changing from heating to cooling. The plant on which the operating data is presented is probably the largest reverse-refrigeration heating installation in existence.

Reversed-Refrigeration Plant in California. As might be supposed, air is the source of heat of the plant which serves the Westinghouse Electric and Manufacturing

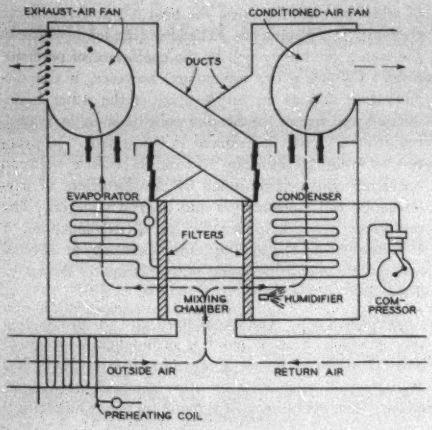

Figure 1. Heating cycle

Company district office building in Emreyville, Calif. The heating equipment consists of two $7\frac{1}{2}$-horsepower compressors, extended-surface evaporators of the type commonly used in air-conditioning work, and air-cooled, extended-surface condensers, a conditioned-air fan, and an exhaust-air fan (Figures 1 and 2).

Winter operation (Figure 1) is as follows. Air drawn in from outdoors and air returned from the air-conditioned space mix in the mixing chamber in about equal proportions and divide into two streams. One of these streams flows through a set of filters, then over the evaporator where the air gives up heat to the refrigerant in the evaporator. The air then passes through the open dampers into the exhaust-air fan which discharges the air to the outdoors. The other stream flows over the other set of filters, then over the condenser, which heats the air, after which it passes through the open dampers to the conditioned-air fan which delivers the air to the ducts leading to the air-conditioned space. When the outdoor temperature falls below 35 degrees Fahrenheit a thermostatically controlled valve admits city water to the preheating coil. The city water being at a temperature of around 60 degrees Fahrenheit adds sufficient heat to the incoming outdoor air to prevent the formation of frost at the evaporator. With an outdoor temperature of 35 degrees Fahrenheit, the air delivered to the air-conditioned space leaves the condenser at 90 degrees Fahrenheit, and the coefficient of performance is approximately 5.

There may be some doubt as to how it is possible to obtain such a high coefficient of performance in view of what was said previously concerning the outdoor temperature. The answer is the mixing chamber. The temperature of the air in this chamber is higher than that of the outdoor air and yet lower than that of the air returned from the air-conditioned space. The result is that the evaporating temperature is higher than would be the case if only outdoor air were circulated over it, and the condensing temperature is lower than it would be if only indoor air were circulated over it. By thus introducing and discarding the air needed for ventilation (It is made to pass first over the condenser and then, when it is discharged, over the evaporator.) most of the heat is regained at the evaporator that was given up to the ventilation air at the condenser.

When weather conditions are such as to require cooling, a thermostat located within the building changes the positions of the two sets of dampers, closing the one and opening the other. Figure 2 shows the dampers thus manipulated. In this cycle, the cooled air from the evaporators is delivered to the air-conditioned space by the conditioned-air fan, and the air from the condensers is discharged to the outdoors by the exhaust-air fan.

An effort was made to obtain operating data on this plant, but inasmuch as the equipment very often is called upon to furnish heat in the morning and cooling in the afternoon of the same day, the watt-hour meter readings do not reveal the energy consumed for heating alone. For the purpose of determining costs, it might prove worth while to install two watt-hour meters, one for the heating cycle, and the other for the cooling. Switching from one meter to the other could be accomplished by a suitable device attached to the damper-operating motor.

Reversed-Refrigeration Plant in Connecticut. Anyone having only a meager knowledge of reversed refrigeration would readily agree that the last place he would look for a reversed-refrigeration plant would be in New England. Yet, what is probably the largest such heating plant in the world is installed in the new administration building of the United Illuminating Company, New

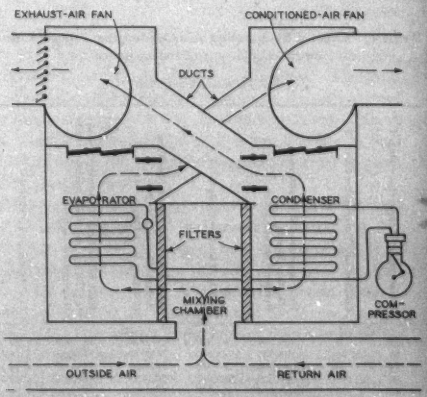

Figure 2. Cooling cycle

Haven, Conn. This is made possible because of a large underground body of fresh water, having a temperature which deviates very little from 58 degrees Fahrenheit throughout the year. Figure 3 shows the refrigeration equipment of this plant.

Six well pumps having a combined capacity of 600 gallons per minute draw water from underground and deliver it to a large sand-settling tank (Figure 4). From here the water flows over a weir, to which is connected an integrating meter, to a second tank. Another pump takes water from this tank and delivers it to one or more of eight water coolers, which are the evaporators of the refrigerating system. In these coolers, the water is reduced in temperature and is then discharged to the sewer. The heat removed from the water is raised in temperature and transferred to a closed hot-water-heating system by one or more of eight 40-horsepower, hermetically sealed, water-cooled condensing units. A pump in this water circuit circulates the water through the eight condensers in series and delivers the water to the air-conditioning units located throughout the building. After passing through all of the air-conditioning units, the water is returned to the first condenser.

Figure 3. Refrigeration equipment in the plant of the United Illuminating Company, New Haven, Conn.

It was stated that the condensers are connected in series. This was done to increase the coefficient of performance. With this arrangement, each condenser raises the water temperature several degrees, and only the end condenser is operated at the final condensing temperature and pressure. If the condensers were connected in parallel, each condenser would have to operate at a final condensing temperature such as to give the desired heating-water temperature.

The heating system was designed on the basis of delivering water 124 degrees Fahrenheit to the heating units when the outdoor temperature is 20 degrees. For outdoor temperatures below this value, the temperature of the heating water is increased, and reaches a maximum of 135 degrees when the outdoor temperature is zero. For temperatures above 20 degrees, the heating-water temperature is lower than 124 degrees.

Control of the condensing units is obtained through an outdoor compensated type of thermostat located in the heating-water circuit. This thermostat, through a step controller, turns on or off the condensing units as required. When a condensing unit is shut down, the water continues to flow through the condenser without any added heat, but the flow of water through the cooler is stopped.

When cooling is required, the equipment operates as a conventional summer air-conditioning plant, the cooled water from the evaporators being delivered to the air-conditioning units, and the condenser water discarded.

Summary of Operating Data. The data on the reverse-refrigeration plant of the United Illuminating Company here presented are for the heating season of from December 1, 1940, through March 31, 1941. The month of November 1940, is excluded because data are not available for the whole month.

Table II shows the hours of operation of the compres-

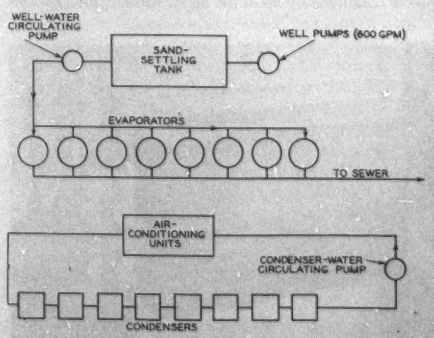

Figure 4. Heat flow in the United Illuminating Company plant

sors and the per cent of available compressor-hours versus degree-days. This table was compiled from the daily readings of hour meters. Provision is made whereby the sequence of operation of the compressors can be changed so that the hours of operation will be about the same for each compressor. The degree-days were obtained from the local weather bureau.

It might be inferred from Table II that the plant is oversized. This is not the case, however, because the full load is not imposed upon the plant 24 hours a day. Quite often the ventilation fan is in operation only during the day. This fan draws in a large volume of outside air representing a considerable portion of the heating load. Also, an additional heavy load is imposed upon the plant from the garage area when the doors are opened to allow the trucks and cars to depart and return. This traffic is heaviest during the morning and evening, although a considerable number of vehicles go in and out during the noon hour. This load is of such short duration, however, that it has little effect on the total hours of operation of the plant. For the heating season in question, the records show that the maximum number of compressors in operation at any one time was five.

In Table III are shown the gallons of water used, kilowatt-hours consumed, and the coefficient of performance for each month of the heating season. The amount of water used was obtained from daily readings of an integrating flow meter. The figures in the "temperature-difference" column were obtained from recording thermometer charts covering a two-month period. The temperature of the well water was found to be practically constant at 57½ degrees Fahrenheit. The average temperature of the outlet water was found to be approximately 51 degrees, making a difference of 6.5 degrees.

Allowance is made for the kilowatt-hours consumed by certain auxiliary motors which would be necessary in a conventional heating plant. The figures in the "net" column of Table III, therefore, show the total power consumed by all of the apparatus required by the reversed-cycle heating plant, including well-pump motors, condenser-water-pump motors, and booster-pump motors. Power required by the ventilation fan is metered separately and is not included.

Table II. Compressor-Hours Operation and Per Cent of Available Hours Versus Degree-Days

Month	Compressor-Hours	Per Cent of Available Hours	Degree-Days
December 1940	1,470	24.7	912
January 1941	1,577	26.5	1,184
February 1941	1,282	23.8	985
March 1941	1,456	24.5	956

Table III. Coefficient of Performance for Heating Season

Month	Well Water Used (1,000 Gallons)	Temperature Difference Deg. F	Heat From Well Water (100,000 BTU)	Net Kwhr	Heat From Electric Energy (100,000 BTU)	Total Heating Effect (100,000 BTU)	COP
December 1940	10,380	6.5	5,620	81,915	2,800	8,420	3.00
January 1941	11,480	6.5	6,230	86,615	2,960	9,190	3.10
February 1941	9,460	6.5	5,120	77,780	2,660	7,780	2.92
March 1941	9,750	6.5	5,275	81,215	2,780	8,055	2.90

Calculation of the coefficient of performance is:

$$\text{(Heat from well water)} = \text{(Gallons of well water) (temperature difference) } 8.33$$

$$\text{(Heat from electric energy)} = \text{(kwhrs) } 3,415$$

$$COP = \frac{\text{(Heat from well water)} + \text{(Heat from electrical energy)}}{\text{(Heat from electrical energy)}}$$

The average coefficient of performance for the entire season is 2.98. This means that almost three times as much heat is obtained from this plant as would be obtained from direct resistance heating.

Residence Application. For residences and small offices a self-contained, portable heating and cooling unit known as the Mobilaire (Figure 5) has been made available. It can be installed in any standard window, requires neither water nor drain connections, and plugs into an appliance outlet. It has sufficient capacity to heat a single room with an outdoor temperature above 40 degrees Fahrenheit. Heating or cooling is selected simply by operating a special four-way valve. This new type of unit is mounted in the window so that one coil is outdoors and the other coil is indoors.

The heating capacity of this unit is 6,600 Btu per hour when the outdoor temperature is 60 degrees Fahrenheit and the indoor temperature is 75. The compressor motor draws 850 watts under these conditions, resulting in a coefficient of performance of 2.28. When used for cooling, this unit can cool at the rate of 6,000 Btu per hour with an outdoor temperature of 95 and an indoor temperature of 80.

Figure 5. The Mobilaire

Carrier-Current Relaying and Communication on the TVA System

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Carrier pilot relaying and carrier-telephone communication have been installed to meet the difficult requirements of relaying and intrasystem communication on the extensive Tennessee Valley Authority system. Eight power-line carrier-telephone channels which can be interconnected at many points and carrier pilot relaying on 20 high-voltage transmission lines help to expedite the multipurpose operating procedures of the TVA. This article gives reasons for the selection of carrier relaying and communication and presents an analysis of their application, of the difficulties encountered, and of their over-all performance under service conditions.

THE Tennessee Valley Authority was formed by an Act of Congress in 1933. The Wilson Dam hydroelectric plant, which was begun in 1918 as a national defense measure and completed in 1925 with an installed capacity of 184,000 kw, was turned over to the Authority. The Act creating the Authority made mandatory the immediate construction of Norris Dam and transmission-line connections between dams. This was to constitute a beginning of a complete development of the Tennessee River from its confluence with the Ohio River to its tributaries in the Great Smoky Mountains, a distance of approximately 600 miles.

The Tennessee River is formed by a junction of two main tributaries. Three other main tributaries join the stream within approximately 100 miles. All of these principal tributaries originate on the western slope of the Appalachian Mountains. This area has a high annual rainfall averaging approximately 120 inches, most of which occurs in a short period of time each year. The steep slope of the terrain results in very rapid run-off. The deep gorges through which these tributaries flow offered possibilities of immense water storage by means of high dams across the gorges. Storage of water within these gorges during the rainy season offered a means of flood prevention down stream. Subsequent emptying of the reservoirs would maintain stream flow in the lower reaches of the river during the dry months for navigation. The water could be used for power generation at the storage dams and at all other dams located downstream.

The main stream of the river system courses through the flatter area toward the Mississippi delta. This area has an annual rainfall of approximately 60 inches. The terrain necessitated that navigational developments be made by means of a series of comparatively shallow pools. A great amount of storage capacity was not required for flood control due to a smaller annual rainfall, a somewhat better distribution of this rain through the year, and the slower run-off of the water shed. Power generating plants at these low-head dams would be of the run-of-river type.

The development required that dams be designed and operated primarily for navigation and flood control, and that all power possible be generated by the water available, as long as it did not conflict with the primary purposes of the development. The disposal of the power generated would require the construction of high-voltage transmission lines to connect the hydroelectric generating stations with each other, to heavy load areas in the Tennessee Valley, and to interconnect with other electric utilities within transmission distance of the hydroelectric generating stations.

It was recognized that the limitations imposed by navigation and flood control on power generation at the tributary storage dams and on the run-of-river hydroelectric generating stations would necessitate the transmission of large quantities of power between the two ends of the system. During the rainy months when water would be impounded in the storage reservoirs for flood prevention and for later release for navigation, most of the loads in the eastern area would be supplied from the run-of-river hydroelectric generating stations downstream. During the dry season when water would be released from the storage dams, the generation from the downstream hydroelectric generating stations would be at the minimum for the year; and the long-distance power transmission would be reduced. These seasonal peak loadings expected on transmission circuits between the storage and run-of-river hydroelectric generating stations would require these circuits to be loaded at times to a value near their steady-state stability limit; otherwise, a considerable investment would be made in transmission capacity which would be utilized only a portion of the year.

Satisfactory operation of such a transmission system was not to be expected, unless any fault which should occur on a transmission line and which might result in

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instability under critical loading conditions was disconnected in a very short time. Initial studies on the network analyzer indicated that faults on the principal 154-kv transmission circuits, involving all three phase conductors, must be disconnected from the system within ten cycles on a 60-cycle basis, and that faults of any nature on these transmission circuits, excepting single phase-to-ground faults, must be disconnected within 12 cycles. The oil circuit breaker selected for use on the 154-kv transmission system were of eight-cycle interrupting time. This imposed a limitation on the selection of protective relays, in that the relays must operate to close contact upon the occurrence of a three-phase fault in two cycles or less, and for any type of fault in four cycles or less. This operating time could be met only by the use of instantaneous relays in combination with some means of comparing the terminal conditions at the ends of the line by a pilot circuit. The use of carrier signal superimposed on the protected line offered the most reliable means of comparing terminal conditions, since the continuity of the blocking circuit would be substantially the same as the line to be protected.

The dispatching operation at the various dams and on the electric transmission system would require heavy communication traffic which, together with the long distances involved, presented a large problem in the supplying of communication facilities. To maintain reliable and continuous communication with dams and switching stations at isolated locations, more than one method or routing of communication channels would be necessary. The use of the power lines for a part of the communication system was indicated by requirements of economy and speed of establishing contacts between stations, and by the fact that hazards to carrier and wire circuits were so dissimilar that a combination of both would give the most nearly continuous service.

Provision was necessary for the transmission of metering impulses from the interconnection points to various hydroelectric generating stations, so that maximum flexibility in operation could be obtained by tie-line load regulation. A feasible method for accomplishing this consisted of utilizing the carrier facilities for the transmission of these impulses in common with other uses. The facilities necessary for carrier communication, pilot relaying, and telemetering are similar. Obviously, one could expect economies in engineering, construction, maintenance, and operation by considering these allied carrier functions as a single problem.

All relaying schemes available for protection of long transmission lines use a three-phase potential source for their operation. The combined use of capacity coupling for connection to the transmission conductor of high-frequency circuits for communication, relaying, and telemetering, with the further use of the coupling capacitor for a secondary potential source,[1] offered additional inducement for the selection of carrier channels as the primary means of communication, relaying, and telemetering over the longer circuits.

The growth of the power system has followed very closely the basic ideas for development of the area and interconnection with other utilities. The 110-kv and 154-kv lines, constructed and in service as of September 1, 1941, total 2,386 miles. The hydroelectric generating capacity in service as of this date was 838,000 kw. The salient points in the basic plan of this transmission system are:

1. Two 154-kv lines located on separate rights of way connecting the run-of-stream hydroelectric generating stations on the Tennessee River.

2. The 154-kv lines connecting hydroelectric generating stations on the tributaries to the main river system.

3. High-voltage transmission circuits to concentrated load areas and interconnections with other electric utility systems.

Carrier pilot relays are used on the power transmission lines of this system, and the line conductors are used to establish carrier channels for communication and telemetering in order to gain the advantages of multiple use of equipment in the manner outlined below:

Table I. Summary of TVA Power-Line Carrier Systems

September 1941

	Pilot Relay	Communication
Number of carrier sets	43*	30**
Number of carrier channels	20	8
Number of carrier frequencies	15	9
Average number of carrier sets per channel	2.05	3.7
Shortest carrier channel in miles	15.5	149
Longest carrier channel in miles	220	283
Average length of carrier channel in miles	62	173
Total length of carrier channels in miles	1,240*	1,384
Total miles of channel used in conjunction with telemetering	195	0
Total miles of channel equipped to provide point-to-point emergency communication	1,045	0
Total number of set-years operation	103	86
Average supply power input in watts	255	975
Minimum carrier power output in watts	15	10
Maximum carrier power output in watts	30	150
Average carrier power output in watts	29	78
Average number of vacuum tubes per set	7	33
Number of coupling capacitor assemblies	43	76
Number of line tuning units	43	40
Number of line traps	43	72

* Two of these sets are on channels jointly owned with interconnecting power companies. Channel mileage is not included for these two tie lines.

** Mobile and portable communication sets not included.

1. Pilot relaying is used on all 154-kv tie lines of the primary system with one exception, which will probably be converted in the immediate future to carrier operation. Several of the 110-kv transmission lines which are used as principal tie lines are equipped with pilot relaying. Carrier is used for the pilot circuit on longer lines.

2. With few exceptions, the hydroelectric generating stations and principal switching stations have both carrier and metallic-circuit communication channels provided. The exceptions are stations where the short distances to the system load-dispatching office and the availability of several separately routed metallic channels insure reliable communication.

3. Both metallic circuits and carrier channels are used for telemetering. All carrier installations are made so that the telemetering function can be added to existing equipment with minor changes. This addition would use either the relay blocking channel or a separate frequency on the line.

4. All coupling capacitors used in the relay carrier channels also function as a part of a resonant potential network.[1] These are used as line potential sources for synchronizing and voltage indication. The two coupling capacitors used in the carrier-communication channels are used also as a part of resonant-frequency-potential sources in many cases which—in combination with the one source from the relay capacitor—furnish three-phase potential for relays and instruments.

Table I shows the extent to which carrier channels have been used on the system.

I. CARRIER RELAYING

The data on carrier relaying contained in this article are intended to show why it was selected, its application to various circuits, some of the earlier difficulties encountered, and its over-all performance under service conditions. No attempt is made to discuss the technical aspects of different circuits which have been used in both the protective relay and blocking channels.

Several different types of equipment were available from various manufacturers at the time the initial installation was made. All of these types were similar to the extent that the carrier circuit was held ready for instantaneous service, to start the blocking signal immediately upon operation of instantaneous fault-detecting relays at a line terminal; carrier transmission over a circuit was stopped by operation of directional relays, indicating that fault condition was internal to the line; and the initiation and removal of a carrier signal—without the instantaneous fault-detecting relay having reset—established a tripping circuit to breakers at all line terminals. The tripping circuits could be set up in a lapsed time from the inception of a fault of 0.75 to 4 cycles. The relaying equipment consisted of the following general types, each of which could be supplied with out-of-step blocking features, if desired:

1. A combination of especially designed impedance relays and directional units for carrier-frequency application. These were faster in operation, but they did not have provision for tripping of the circuit breakers, in the event that carrier-controlled relays were inoperative because of the nature of the disturbance or the failure of equipment.

2. Conventional distance relays, wherein a carrier-frequency signal or other signals were used to operate a device which, in effect, by-passes the definite time imposed in tripping by distance relays on a backup zone. These were slower in setting up the tripping circuit than the relays especially designed for carrier use.

Relay Installations. Figure 1 shows the main 154-kv transmission circuits which are supplied with pilot protection, either by means of telephone conductors or carrier-frequency channels. This transmission diagram shows the length of each line, the maximum load which has been transmitted over the lines for an appreciable period of time, and code symbols designating the type of relays used for each line terminal. The code is as follows:

A—Phase impedance and directional units, together with an instantaneous and a directional overcurrent unit for ground protection, all especially designed for carrier use. Backup protection consists of directional ground relays and phase overcurrent relays,

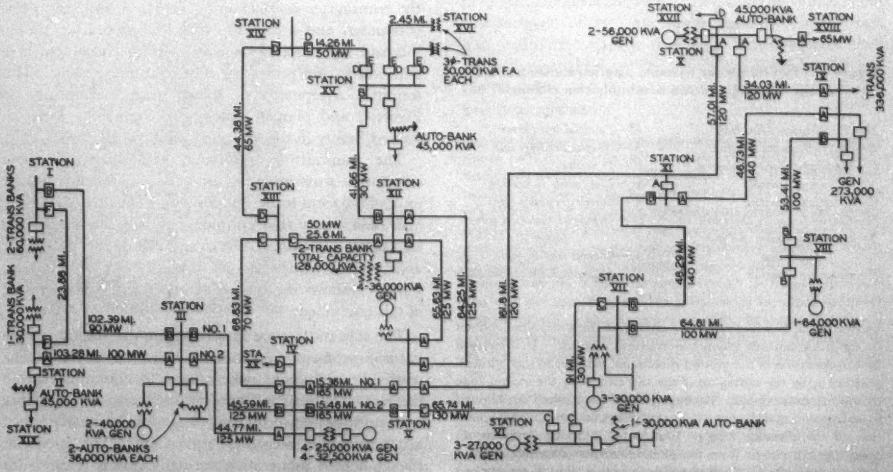


Figure 1. Diagram of 154-kv transmission system showing location of the five different applications of pilot-relay protection

containing both instantaneous and induction elements, which are directionally controlled when necessary. Transmission of carrier is started by the opening of contacts on an impedance element or the instantaneous ground element, and is stopped by operation of the phase or ground-directional unit. Out-of-step blocking is accomplished by holding carrier on continuously during a three-phase disturbance which originated external to the line.

B—Standard three-zone impedance relays for each phase, together with a ground element consisting of two high-speed overcurrent units and a ground-directional unit. Transmission of carrier signal is initiated by the closing of the third-zone contact or the instantaneous ground overcurrent element. It is stopped by the operation of the ground-directional element to the "closed" position or by the setting up of the trip circuit by the second zone of the distance relays. Backup ground protection is obtained from conventional directional ground relays and the normal operation of the distance relays. Out-of-step blocking functions to open the trip circuit from the phase elements of carrier relays a definite time after a three-phase fault occurs, and is maintained open until the three-phase disturbance has subsided.

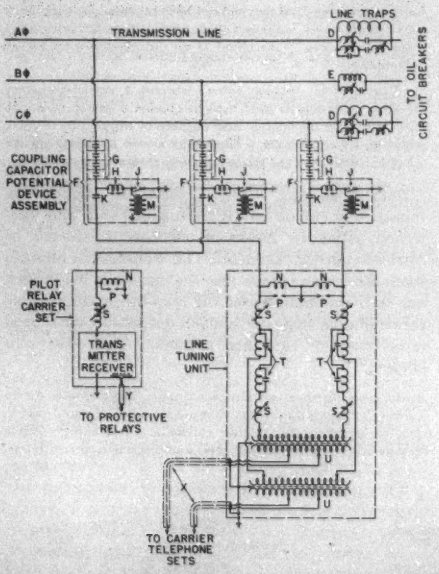


Figure 2. Typical carrier terminal diagram showing coupling of one relaying and two communication channels

D—Two-frequency line trap
E—Single-frequency line trap
F—Coupling-capacitor potential device assembly
G—Coupling capacitors
H—Carrier-frequency choke coil
J—Grounding switch and protective gap
K—Auxiliary capacitor
M—Potential transformer
N—60-cycle drainage coil
P—Protective gap
S—Line-tuning inductance
T—Carrier-frequency traps
U—Impedance matching transformer
X—Coaxial lead-in cable
Y—Multiconductor control cable

C—Three-zone reactance relays using a separate set of phase impedance units for the starting of carrier, and a ground element consisting of two high-speed overcurrent units and one high-speed directional unit. Transmission of carrier is initiated by the opening of the contacts of the separate impedance units, or by the opening of the instantaneous element of the ground relay. It is stopped by the operation of the high-speed ground directional or phase directional unit of the distance relay. Tripping results from the closing of the high-speed induction overcurrent element of the ground unit or the ohm units of the distance relays used for carrier protection. The receiver relay of the carrier system, in effect, by-passes the operation of the timer for this ohm unit. Out-of-step blocking is established by the development of a three-phase fault external to the line. It is maintained during the disturbance by opening the trip circuit from phase carrier or continuing the carrier signal. Backup protection is obtained by the normal functioning of the distance relays and by a conventional directional ground relay.

D—Conventional reactance relays and directional ground relays. No pilot blocking at any time is used.

E—Three-phase voltage-restrained directional relay in combination with a high-speed directional ground relay. Continuous blocking is obtained by means of a telephone conductor circuit and the station storage battery.

F—Three-zone impedance relays as described for carrier use in *B*, except that blocking is obtained by means of a telephone circuit and actuated by potential from station storage batteries.

It is to be noted that carrier blocking is used on all of these lines rather than metallic circuits, except where a shielded cable is available between the two line terminals, and where the annual cost of the relays and the cable is competitive with the annual cost of the equipment necessary for carrier protection.

Carrier Terminal Equipment. The installation at each terminal of the line consists of a high-frequency transmitter and receiver unit, a coupling capacitor between the transmitter–receiver unit and the transmission line conductor, and a line trap located between the station bus and the coupling capacitor. This equipment is in addition to the protective relays for the circuit. This terminal equipment is shown diagrammatically in Figure 2 and photographically in Figure 8. It is described briefly in the following paragraphs.

The transmitting, receiving, and surge protection equipment is assembled in an outdoor cabinet, is usually located adjacent to the coupling unit, and is designed for operation at any selected frequency between 50 and 150 kilocycles. It utilizes one transmission-line conductor and ground return for its circuit. The photograph, Figure 3, shows the typical arrangement and mounting of this equipment.

The transmitters are supplied from the station storage battery or from a rectified a-c power source. The rectifying equipment, where used, is contained within the set. The set consists of an oscillator and amplifier with sufficient power output to produce a reliable signal at the remote receiving equipment. The oscillator circuit is held inoperative normally. It is released for oscillation by the operation of the protective relays, by

telemetering equipment where such is used, by controls from emergency carrier-telephone attachment, or by the test button. The transmitters are controlled by one of the two following methods:

1. Removing a high negative bias from the grid circuit by the opening of the protective-relay contact or other contacts associated with telemetering, testing, or emergency telephone equipment.

2. Changing the potential supply in the plate of the oscillator tube by the closing of contacts in the protective relays, telephone equipment, test button, or telemetering equipment.

The receiving element consists of a detector circuit and sufficient amplification to maintain a reliable signal output during the most unfavorable conditions for carrier transmission over the power conductor from the remote transmitter. A drainage circuit is provided, so that a maximum limit is placed on the signal supplied to the receiver relay. The receivers are selective, to the extent that erroneous operation will not result from another signal spaced five kilocycles or more from its adjustment.

The capacitors used for carrier coupling consist of several units in series, rated for phase-to-neutral voltage of the power system. A tap between sections of the capacitor stack supplies energy to a medium-voltage potential transformer through a carrier-frequency choke.

Figure 3. Typical carrier - relaying transmitter - receiver set

This potential transformer, together with adjustable inductance and capacitance, supplies a 60-cycle 69-volt or 115-volt potential source which is inphase with the primary phase-to-ground potential. This unit is used to supply potential for synchronizing and—in combination with other similar units where carrier communication is installed—for potential to protective relays and meters.[1]

Line traps are used to prevent the carrier channel from becoming short-circuited during an external phase-to-ground fault, and to block effectively the flow of energy of the carrier frequency or frequencies from the station bus—thus confining the output of the transmitter to the circuit to which it is connected. The use of these devices reduces the power required to maintain an effective blocking signal and, at the same time, prevents energy at or near the tuned frequency of the circuit from entering from another circuit. The same frequency can be used on several transmission lines as long as the lines are physically located so that there is no interference because of coupling between them. The inductive component of the line traps consists of power conductors, with current-carrying capacity equal to that of the line, wound on a porcelain cylinder. Adjustable capacitors are used for tuning and are mounted inside the porcelain cylinder. The capacitor units are made watertight, and the ends of the porcelain cylinders are covered over in such a manner as to prevent the entrance of birds.

Application Problems Encountered. After the installation of the first few units of carrier relays, tests were made to check this equipment by placing faults within and external to carrier-protected lines. These tests were arranged to represent, as nearly as possible, actual fault conditions, by using arcing faults rather than solid metallic faults, and by using a separate oil circuit breaker to connect a fault to the line. The tests disclosed certain conditions under which satisfactory performance was not obtained. Some of these conditions resulted from the inability of the instrument transformer secondary circuits to portray accurately the conditions on the primary line. The instrument transformers supplying the relays were, in all cases, bushing-type current transformers. Both station-type potential transformers and coupling-capacitor potential networks were used for potential supply. The difficulties encountered and the remedies used for their elimination are summarized briefly as follows:

1. The resonant-circuit potential device[1] under fault conditions would oscillate, producing a very unstable voltage, both as to magnitude and frequency. The output from these devices contained harmonics of a high order and of a very great magnitude. It was also found that, when energizing an unfaulted line section, normal secondary potential was not re-established so fast as current was built up in the current-transformer secondary circuit. These difficulties were eliminated by rebuilding the potential devices to obtain stable performance under all normal conditions and with any secondary burden in the range for which the device was calibrated. The carrier-relay directional-unit circuit was modified to some extent and adjusted to prevent tripping of the oil circuit breaker by these relays when energizing an unfaulted line.

2. It was found that the unsymmetrical pole opening or closing of an oil circuit breaker, which results in establishing or maintaining a tie for a short interval of time as a two-phase and neutral or single-phase and neutral connection, would cause operation of the carrier equipment. This condition, of course, is identical on a grounded wye system with an internal phase-to-ground fault on

the line. This was eliminated by the use of an overcurrent induction element in the ground trip circuit so that a minimum of approximately two cycles was required to trip by carrier ground relay.

3. It was found that the energy emitted from the arc caused by opening an oil circuit breaker carrying heavy current could adversely affect the received carrier signal to such an extent that it would be destroyed. This permitted incorrect tripping of an unfaulted circuit adjacent to one wherein the oil circuit breaker was disconnecting a faulted line. This defect was corrected by the addition of an auxiliary relay which functioned to prevent the operation of the receiver relay on loss of carrier signal after carrier had been received continuously for approximately four cycles. The auxiliary relay would then release the receiver relay for tripping after a definite time of approximately four cycles. This unit does not interfere with the normal performance of carrier for an internal fault; but, in the event of an external fault, carrier is made inoperative by the time arcing begins in a breaker and is held inoperative for sufficient time to override arcing within the breaker. The carrier-receiver unit was readjusted, and its surge protection was modified to minimize the likelihood of detuning the circuit.

Similar conditions could be obtained by the opening of air-break switches; however, the likelihood that an air-break switch operation would occur coincidental with a fault is so remote that the readjustment of the receiver equipment was considered satisfactory for the elimination of this possibility.

4. It was found that operation of air-break switches on a high-voltage bus also caused a momentary drop in potential, supplied from a resonant-circuit potential device. This reduction in voltage did not last for more than $1^1/_2$ cycles, but it was of such magnitude at times as to cause incorrect tripping by carrier relaying on a heavily loaded line. The only remedy employed for this purpose was to maintain settings of the carrier relaying high enough to minimize the possibility of such occurrence.

Investigations and operating experience also revealed conditions which necessitated some modification in equipment. On long circuits, like the line between stations V, XI, and X, it was found that, where a combined phase and ground-directional element was used, it was necessary to remove all phase torque, as well as restraint, from the phase unit in order that the element could operate properly. The charging current for the line exerted more torque on the phase unit than did the ground unit for a metallic ground fault at the remote end of the line.

It was also found undesirable to have complete ground preference to the extent that tripping by phase relays was prevented after carrier was initiated by the ground element. Multiple phase and ground faults may have a value of ground current sufficient to start carrier by the ground element but insufficient to trip by the ground element. This condition was overcome by rearranging the circuit so that a ground-directional element, as sensitive in setting as the element which started transmission of carrier, would release ground preference for tripping either by the ground-tripping overcurrent element or the phase relays.

It has also been found that, because of the characteristics of bushing-type current transformers and the necessary secondary leads and wiring, a residual current may be present during an interphase fault not involving ground. At times, this residual current is of such magnitude as to start transmission of carrier. A ground-directional element is inoperative for removal of carrier under this condition. This problem is being studied in an endeavor to eliminate this condition. Figure 4 shows an oscillogram taken when closing into an ungrounded fault between two phase conductors. The residual current in the ground carrier-starting element shown on trace 4 was of sufficient magnitude to start and maintain a carrier-blocking signal for several cycles. On similar test, but without complete oscillographic information, the line breakers did not trip during the fault.

Performance Record. The initial carrier installations were made in 1937 on the IV-V and the V-XI-X lines. Additional terminals have been placed in service at frequent intervals since that time, as shown in Figure 7. The operating record of this equipment submitted in Table II is limited to that period between January 1, 1939, and September 1, 1941. The small number of terminals in service prior to 1939 and the limited oscillographic information preclude the inclusion of earlier operations in a detailed analysis of equipment performance.

Automatic oscillographs are in use at most of the hydroelectric generating stations. These are connected in such a manner as to obtain the maximum amount of information on the performance of carrier relaying on the main 154-kv transmission circuits. The data given in the tabulation on the type of fault, its location, and the performances of relays on internal and external faults, were deduced from the automatic oscillograph records.

The symbols given in Table II for causes for incorrect performance on internal faults are explained as follows:

A. The fault was cleared at both terminals by backup relays. The failure to trip by the carrier-blocked high-speed relays was found to have resulted from incorrect connection of the ground-directional element. Ground preference prevented operation by the carrier phase relays.

B. A broken wire within the relay and inside the insulation was found subsequent to the second incorrect tripping. This broken lead was in such a position that tripping by the carrier-controlled elements was prevented. The faults were cleared in both cases by backup relays.

C. A three-phase fault was cleared at both terminals by backup distance relays. A carrier-blocking signal was maintained throughout the fault. No transformer neutral current was present. It was concluded that failure to trip properly resulted from the operation of the ground carrier-starting element, because of characteristics of the bushing current transformers and their performance under fault conditions. This possibility was verified by staged tests. The oscillogram, Figure 4, was taken during these tests.

D. Maladjustment of two circuit contacts prevented the removal of carrier-blocking signal. The fault was cleared by backup relays.

E. The fault was from two-phase conductors to ground near station XI and was cleared by backup ground relays. It was

deduced that failure to trip by the carrier relays resulted from insufficient torque to close the contacts of the potential-polarized ground-directional unit at station IX terminal, even though the ground current was of sufficient magnitude that the ground element for starting carrier would pick up. The ground preference held the carrier phase elements inoperative. This case may have been an operation similar to *C*.

F. A three-phase-to-ground fault, wherein the magnitude of ground fault current in the fault started transmission of carrier by

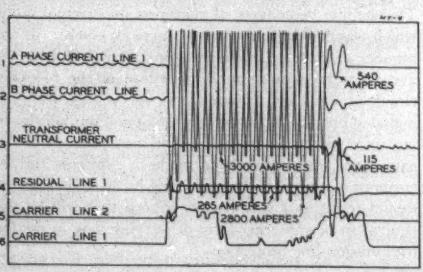


Figure 4. Oscillogram taken during staged tests at station III

Trace 4 is the residual current circuit from bushing-type current transformers located in the faulted line oil circuit breaker. Trace 3 shows the absence of ground current during the fault. The fault was cleared by the test breaker by means of overcurrent relays. Carrier blocking was not removed from the faulted line until approximately five cycles after the fault was started, as shown on trace 6. Both terminals of the line tripped correctly after the time delay

the ground element, but did not result in tripping by the ground element. The ground-preference characteristic prevented the tripping by the phase elements.

G. A permanent single-phase-to-ground fault between the overhead ground wire and *A* phase conductor failed to trip by the carrier-controlled relays. The load and charging current on the line were such that a combination phase and ground-directional relay did not operate to remove carrier blocking and permit tripping. The fault was cleared by backup ground relays. The oil circuit breakers were not tripped simultaneously.

H. Two faults occurred in the same afternoon on the line. Each was tripped correctly at one terminal by carrier relay operation. The other terminal was cleared in each case by the operation of backup relays. The failure to trip properly at the second terminal was found to have resulted from mechanical trouble in the auxiliary seal-in unit of the carrier relay.

The symbols in Table II for causes of incorrect tripping on external faults are explained as follows:

(*a*). Both ends of the line were tripped simultaneously with an external ground fault. The ground-directional element at the adjacent terminal was found to be connected incorrectly. The incorrect connection resulted from temporary wiring used while additions were being made at the locations involved.

(*b*). Incorrect tripping occurred at the end remote from an external fault. A line trap was subsequently found to have caused a received carrier signal below the operating level of the receiver relay. The line-trap failure resulted, in one case, from condensation within the tuning-capacitor unit and, in the other, from wet birds' nests which short-circuited the tuning-capacitor unit in the trap.

(*c*). Operation by all three-phase elements on an out-of-step condition. The electrical center of the disturbance was just beyond the remote terminal of the line. No definite cause for this incorrect operation has been established.

(*d*). Defective resistor, in the receiver relay at the terminal remote from the fault, prevented the carrier signal from holding open the receiver-relay trip circuit.

(*e*). Tripping circuit was apparently set up during arcing of the breaker on an adjacent section, since tripping on this line occurred slightly later than on the faulted line.

(*f*). The breaker at one line terminal was tripped by differential-relay operation on a fault within the station. The remote end of the line was tripped immediately following the opening of the first breaker (by differential relay) at the remote station.

(*g*). The end of the line remote from a three-phase external fault was tripped immediately through the second zone of distance relays, despite carrier blocking. Subsequent investigation revealed that the timer for this zone was stuck in the "closed" position. It was concluded that a previous disturbance, external to the reach of this zone, had caused operation of the timer which failed to reset. The type of contacts was changed to a different design to prevent recurrence.

(*h*). These operations took place on power swings following faults. They probably should not be charged to the protective relays as incorrect performance, since the application, rather than the equipment, is the cause. From the length of line and loads transmitted, it is obvious that very little difference exists between load impedance and fault impedance. Since the line has three terminals, a tripping value can be reached at station V terminal on power input, before the output from the line at either station XI or X will cause transmission of carrier. This line will be broken at station XI when the permanent switchyard at this point is placed in service.

Remedial measures have been worked out in conjunction with the manufacturers and put into effect; these should eliminate most of the incorrect operations resulting from malperformance of carrier-blocking channels, of relays as applied to the transmission circuit, and of instrument transformers in portraying the transmission-line conditions to the relays. The backup distance relays are now connected in such a manner that out-of-step blocking does not affect their operation, and all zones are normally in service at all times. The incorrect connections, which resulted in failure to trip on internal faults and in incorrect tripping on external faults, were temporary connections, used while extensions or changes were in progress at the stations involved.

Conclusions. The results obtained from the carrier relays have well justified their selection. The critical loading of transmission circuits, due to recent abnormal loads and drouth, has clearly demonstrated the necessity for high-speed clearing of the main transmission circuits during faults, if instability is to be avoided. In addition, it has been demonstrated that lower-voltage transmission or primary distribution circuits, in many cases, must be equipped with some form of protection which will clear a fault on any portion of these circuits within a very few cycles.

Based on the experience recorded in this paper and under the existing system requirements, the following

statements appear to be justified. The original assumption that the carrier channel over the power conductor was substantially as reliable as the transmission line has been proved correct. The elimination of conditions which caused detuning of line traps, loss of blocking signal—due to the arc during the opening of an oil circuit breaker on a fault, and rigorous maintenance of the transmitter–receiver equipment will remove, it is believed, further difficulties from the blocking channel.

The performance of distance relays as backup protection and of the backup ground relays has been of great value in disconnecting a faulted line, when carrier equipment was not available for service due to maintenance and repair, during out-of-step conditions, or when the carrier relaying failed to operate properly. It has been determined that the distance relays with carrier blocking are more satisfactory than the especially designed carrier units which do not include backup phase protection, unless separate distance relays are used for this purpose. These distance relays should be in normal service at all possible times and should have no restriction in their performance by out-of-step blocking. Should the electrical neutral of an out-of-step condition develop within the reach of zone 1 of the distance relays, the immediate disconnection of this circuit is preferable to a continued out-of-step condition on the system.

Table II. Operating Record of Carrier Relays

January 1939 to September 1941

Tie Lines between Stations	Date in Service	Faults on Lines				Incorrect Internal			Incorrect External	
		Total	3-Phase	2-Phase-to-Ground	1-Phase-to-Ground	No.	Per Cent	Cause	No.	Cause
III to II	July '38	2	0	1	1	2	100	*A*(2)	0	
III to I	June '40	3	0	0	3	0	0		0	
IV to III—No. 1	May '40	3	1	0	2	1	33	*B*	1	*a*
IV to III—No. 2	Feb. '40	2	1	0	1	1	50	*C*	0	
IV to XIII	Jan. '41	7	2	2	3	0	0		0	
IV to V—No. 1	Mar. '37	2	1	1	0	0	0		0	
IV to V—No. 2	July '40	0	0	0	0	0	—		0	
V to XII—No. 1	Mar. '40	2	0	0	2	0	0		0	*b*
V to XII—No. 2	June '38	5	2	2	1	1	20	*D*	1	
V to VI	Dec. '38	15	2	5	8	1	7	*C*	1	*a*
XI to IX	Nov. '38	6	3	2	1	3	50	*E*	1	*c*
VII to XI	Apr. '39	5	2	1	2	1	20	*F*	4	*a, c, f, d*
V to XI to X	Mar. '37	5	1	1	3	1	33	*G*	8	*g*(1), *h*(7)
VIII to IX	Aug. '41	0	0	0	0	0	—		1	*f*
IX to X	Nov. '38	3	0	2	1	0	0		0	*e*
X to XVIII	July '40	2	0	1	1	0	0		1	*f*
XII to XIII	June '38	2	0	0	2	2	100	*H*	0	*e*
XII to XV	Feb. '41	1	0	0	1	0	0		0	*e*
VII to VI	Dec. '38	15	4	6	5	0	0		1	*b*
VII to VIII	Sept. '40	2	0	1	1	0	0		0	*e*
Total 20 Lines		82	19	25	38	13	16		19	

The 16 per cent incorrect performance of the carrier relays on internal faults, as shown in Table II, is rather large. The failure to trip on internal faults, as a result of incorrect connections, contact adjustments, or mechanical troubles, should not be charged to the carrier-relaying scheme. The elimination of these failures as incorrect performance of the carrier scheme will reduce the number of tripping failures to 8.5 per cent. The removal from the incorrect column of those tripping failures resulting from defects that have been eliminated will further reduce the number of incorrect operations to 2.5 per cent.

Each fault listed in Table II and many others not listed were external to several carrier-protected lines. The definite percentage of operation on external faults which was correct or incorrect cannot be given. If the number of incorrect operations on external faults is reduced to those resulting from failure of the blocking circuit or the relay to function in accordance with the intended operation, the percentage operations which are incorrect will be very small. The modifications of the equipment which have been made to eliminate the recurrence of several of the remaining incorrect operations should result in a performance record that will be the equivalent of any other form of relaying now in use for transmission-line protection.

II. CARRIER COMMUNICATION

There are eight power-line carrier-telephone channels which furnish part of the primary communication service used to expedite operation of the multipurpose dams for flood control, navigation, and power generation. Direct communication channels between key generating and transmission stations provide fast service, and a sufficient number of stations have access to individual channels for efficient utilization of the facilities. Communication reliability is improved by routing circuits over different geographical paths between the same points, by utilizing various types of telephone systems, or by employing different kinds of outside plant facilities. Conditions which cause interruptions in one route, type, or kind of facility do not necessarily affect adversely the service rendered by another, since each possesses different inherent characteristics. A combination of these several methods is used to maintain contact between important operating points. Duplicate carrier-telephone channels are provided between a few important points. Separate transmission lines are used to establish these circuits.

The Tennessee Valley Authority is operating 1,384 miles of carrier-telephone channels and 2,000 miles of open-wire and cable telephone circuits. While much of the general communication service is leased from commercial telephone companies, the power-line carrier-telephone and the wire-telephone systems, which have been closely co-ordinated with each other, furnish the principal means of communication for carrying on multipurpose operations. Each of these several types of communication systems is arranged to supplement the others. These communication circuits are used primarily for interconnecting the various dams, hydroelectric generating stations, switching stations, and load-dispatching offices.

Table I includes data on the carrier-communication network, arranged for comparison with the pilot-relay carrier system.

The arrangement of 30 carrier-telephone sets, connected to eight separate channels (shown in Figure 5), was determined after a study which considered the balance between the reliability and flexibility needed, and the cost of the resulting layout, including the necessity for quick communication between related points in any one area, and provisions for extending the communication system to additional locations. There are approximately 100 telephones directly connected to the 30 carrier-telephone sets. These telephones serve strategic operating locations in the hydroelectric generating stations, such as the control rooms, superintendents' offices, repair shops, and telephone equipment rooms, as well as substation control buildings, offices of division managers and engineers, and district operating superintendents. Control rooms in the hydroelectric generating stations are provided with key-type telephone switchboards to which are connected the carrier-telephone sets and other communication circuits, all of which may be interconnected at these points.

Communication traffic studies are made at intervals to check the adequacy of the communication system and to insure maximum economy in use of the facilities. Electric timing and counting apparatus provides traffic data automatically on each carrier-telephone channel.

Types of System. Two basic types of carrier-communication equipment are used: one called "single-frequency duplex," or "single-frequency automatic simplex,"[1] by respective manufacturers, and another "two-frequency duplex." The single-frequency system uses one carrier frequency for both transmission and reception, while the two-frequency duplex, as its name implies, uses two carrier frequencies.

There are 28 single-frequency sets in use. These sets provide party-line use of the channel, which enables the system load dispatcher to communicate with a number of stations simultaneously, in effect providing a conference connection between the dispatcher and all stations involved, during switching or other operations. Complete control and operation of the single-frequency duplex communication sets are secured from two-wire, dial-type telephones. Voice and carrier signal-actuated relay circuits automatically control the operation of the transmitter and receiver circuits so that transmission of a carrier signal takes place only when voice, dialing, or ringing signals are actually being transmitted. During transmission, the telephone is connected only to the transmitter, and the receiver is blocked. During reception, the telephone is connected only to the receiver so that the transmitter cannot be operated. This automatic voice control of the sending and receiving functions uses electronic relays having no moving parts[3] in seven carrier-telephone sets and a standard telephone-type mechanical relay in the remaining sets. The over-all similarity of the two general types of single-frequency duplex equipment is so close that sets from two manufacturers are now being operated on a common carrier-telephone party-line channel.

The two-frequency system uses one frequency for transmission and reception in one direction, and the other frequency is used for transmission and reception

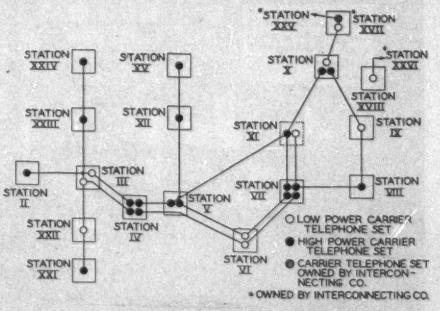


Figure 5. Carrier-telephone channels in operation on the high-voltage transmission lines

in the opposite direction. Both frequencies are continuously transmitted when the sets are in operation. Complete control and operation of the equipment are achieved by using local battery telephones.

The carrier power output of the telephone sets, shown in Figure 5, can be grouped in two general classes. The low-powered sets range from 10 to 25 watts, while the high-powered sets range from 100 to 150 watts. In the case of the single-frequency equipments, it is only necessary to install or remove an amplifier unit in the bottom of the cabinet in order to change the rating of the set from low to high power or vice versa. This unit-type assembly is desirable, since it provides the necessary flexibility for conveniently making changes in the carrier power output of individual sets. One installation of four carrier-telephone sets is shown in Figure 6. The two middle sets are single-frequency duplex equipments having a carrier output of 100 watts each, while the sets on each end are automatic simplex equipments having a carrier output of 150 watts each.

The carrier-communication and carrier-relay systems were installed in several major steps over a period of five years, as shown in the progress chart in Figure 7, which is based on the initial date each carrier unit was placed in operation.

Method of Operation. Each single-frequency duplex carrier-telephone set is equipped to provide six separate selectively rung telephone circuits. This has the advantage of providing more rapid inward and outward service to these points, because it eliminates manual operations by the station operator which normally would

Figure 6. Four single-frequency power-line carrier-telephone sets

be required to set up a telephone connection. The telephone line serving the station operators or the system load dispatchers is arranged electrically to provide a feature called "preferred service," which permits an operator or dispatcher to have priority use of the carrier-telephone channel at all times, as contrasted to other telephone extension lines which receive a busy signal and are automatically locked out during all conversations not involving that particular telephone.

Before dialing on a party line, it is necessary to determine if the channel is in use. On nonpreferred telephone lines, this busy indication is given automatically. On preferred lines, it is necessary to monitor the channel to determine if it is being used. The call is placed by dialing a three-digit number. Within a few seconds after dialing has been completed, a distinctive tone is heard by the calling party, which indicates that the bell of the called telephone is ringing.

Two types of directories have been issued for the carrier-telephone system, namely, a directory printed on colored sheets, corresponding to channel designations, and a color-coded chart. The use of a directory helps to eliminate the dialing of wrong numbers and expedites interconnections of individual channels by furnishing the calling party with specific information for requesting the correct channel and desired number. For example, a station at one end of the system can communicate with a station at the other end of the system, a distance of 382 transmission-line miles, merely by requesting the system load dispatcher to connect the proper channels and dialing the desired number.

Power Supply. The power supply to all carrier-telephone sets installed by the Authority is secured normally from the 115-volt, a-c station service circuit. However, extreme variation or failure of normal power supply does not interrupt communication. An emergency source of a-c power is provided at each point, consisting of a motor alternator operated on the station control battery which is automatically controlled by a motor-starting and transfer panel. This emergency power is available so quickly that only a momentary interruption is noticeable while one is talking over the carrier-telephone channels during a change in the source of power supply. Upon restoration of the normal supply voltage to a value within the satisfactory operating limits of the carrier-telephone sets, the motor alternator is shut down, and the carrier-telephone bus automatically returns to the station service supply.

Emergency power equipment is available at all locations except one, where an early-model single-frequency duplex set is located. Power supply for this set is secured from the station storage battery and a four-unit motor alternator, the 115-volt station service supply not being required. At another point, a motor alternator for emergency power is used jointly by the a-c operated pilot-relay carrier sets and the telephone sets. At two of the hydroelectric generating stations, a motor alternator for emergency power supply is used jointly by the carrier-telephone sets and the load and frequency control equipment.

Cables and Line-Tuning Units. In contrast to all pilot-relay carrier sets being mounted out of doors in weather-

proof cabinets, the carrier-telephone sets are all mounted indoors. The location of the telephone sets varies from a minimum of 250 feet to a maximum of 1,500 feet from the line tuning units. To connect the telephone sets with the line tuning units, two general types of lead-in cable are used:

1. Parallel twin-conductor high-grade rubber-insulated cable covered with a lead sheath.

2. Concentric cable consisting of a stranded special rubber-insulated conductor around which is braided a copper shield covered with a lead sheath or a rubber jacket.

Concentric cable has been used in more recent projects, because its transmission efficiency is greater, and it is somewhat easier to handle during installation.

The lead-in cables are connected to impedance-matching transformers located in weatherproof boxes in the switchyards in order to minimize loss of carrier power at this point. The schematic circuit of a typical two-frequency telephone-line tuning unit is included in Figure 2. A two-frequency line-tuning unit is mounted on the right-hand side of the steel structure supporting the coupling capacitor assemblies in Figure 8, which shows the same principal items of equipment included in Figure 2.

In addition to impedance-matching transformers, the line-tuning unit contains the inductances and parallel resonant circuits necessary for tuning the two coupling capacitors to provide two interphase-coupled, single-frequency carrier channels, each operating on a separate and distinct frequency. The parallel resonant circuits, or trap circuits, are employed to prevent the flow of power, at the frequency to which they are tuned, into other directly connected circuits where it would be undesirable. Protective equipment, consisting of 60-cycle drainage coils, gaps, and grounding switches, shown in Figure 2, is included in the line-tuning unit to protect personnel and apparatus.

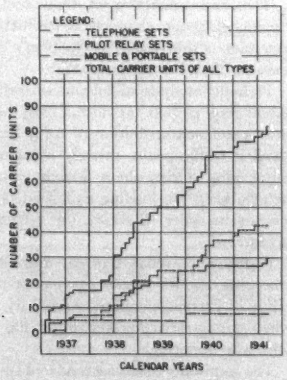


Figure 7. Progress chart showing growth of power-line carrier systems

A single-conductor cable with special rubber insulation is used between the line-tuning unit and each coupling capacitor. Since the voltage on this wire at carrier frequencies is relatively high, and since any variation in carrier-frequency leakage has more pronounced effects in this portion of the carrier circuit than in any other, it is necessary to avoid serious carrier signal-strength variations by minimizing leakage due to dirty insulators, sleet, and rain. The line-tuning units are, therefore, located as close to the coupling capacitors as feasible. In the Tennessee Valley Authority's system, this distance is generally less than ten feet. This conductor is supported on as few insulators as possible to reduce the number of parallel leakage paths to ground and with at least six-inch clearance between other parallel conductors and steel beams in order to keep the stray capacitance to earth as low as possible.

All carrier-telephone channels are coupled to the outside phase wires of the transmission lines with one exception in which a channel operates on the middle phase wire to ground. The carrier-communication frequencies are confined to the transmission line conductors proper by the use of line traps. At intermediate stations, the carrier-communication frequencies are by-passed around the switchyards, so that the switching of power circuits will not disturb the operation of telephone channels.

Portable and Mobile Equipment. The Tennessee Valley Authority has made considerable use of a portable carrier-telephone set which operates from a six-volt storage battery. This portable set weighs 141 pounds. The leg-type supports can be folded back against the sides of the weatherproof housing to provide handles for carrying. This set was used for nearly two years at a large temporary substation, and the savings in communication costs more than offset the original price of the set.

Two general types of carrier receivers have been installed in automobiles:

1. A single-frequency fixed-tuned receiver.

2. A variable-tuned receiver with one band covering a range of 50 to 150 kilocycles.

A variation of the second type of receiver has just been secured, which combines variable tuning in the power-line carrier range in two bands and provides a third band in the medium short-wave radio-frequency range of two to three megacycles for use with radio-telephone sets during emergencies. During normal times, the cars equipped with carrier receivers listen in for messages directed to them during two prearranged five-minute periods each hour. During emergencies, these automobiles leave their carrier receivers in operation continuously when within receiving distance of the channels. Receivers are equipped with noise-suppression circuits

which render the speakers silent when calls are not being received, thus eliminating noises which would otherwise be distracting.

Two-frequency portable carrier-line traps are used for grounding the transmission circuits. These traps weigh only one-tenth as much as standard two-frequency traps

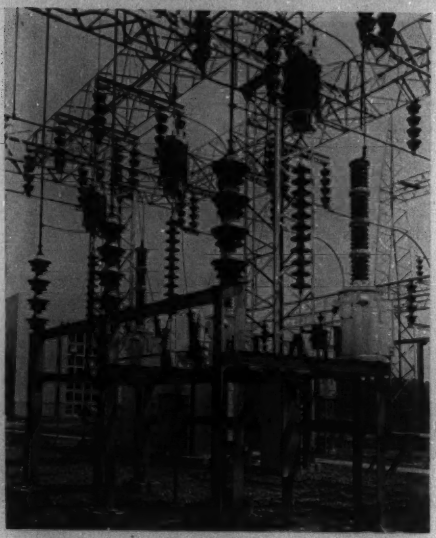


Figure 8. Carrier terminal equipment showing coupling capacitors and line traps for one relaying and two communication channels

and are designed to be connected in series with ground cables required to protect linemen when working on a de-energized power line. This arrangement prevents the short-circuiting of the carrier-telephone circuit and allows uninterrupted use of the channels during power-line repair periods.

Operating Experience. Operating experience with over 100 each of coupling-capacitor assemblies and carrier-line traps indicates that the maintenance of this type of apparatus is comparable to that required on similar high-voltage equipment in the switchyard. Since bird baffles have been added, and the tuning packs made weatherproof in the traps, only one case of trouble has been experienced, which was the result of a cracked porcelain bushing used to insulate one end of a trap through-bolt.

The over-all operation of the carrier telephone sets has been kept at a satisfactory level by following a program of inspection and tests at regular intervals. Checking the operating condition of carrier equipment is expedited by the use of a variety of standard electrical testing apparatus. The analysis of trouble reports, which is made at the completion of the correction of each case of trouble, has permitted modifications to be planned so that minor weak points have been eliminated. The manufacturers of the carrier equipment co-operated closely in working out jointly the carrier application problems, as well as assisting in setting up detailed maintenance instructions.

Even though the principal relay assemblies in all o the carrier-telephone sets are protected by dust covers, it is still necessary to keep the air-intake filters clean, as well as to remove dust from the equipment in dusty locations by means of a vacuum cleaner at periodic intervals. The individual shelves of the carrier-telephone assemblies are capable of being rolled forward from their cabinets and, in some cases, rotated upward and latched in an angle position, so that cleaning and inspection of the underside of the shelf is as convenient as checking the topside.

Conclusions. The conclusions from the preceding facts, as well as from an analysis of operating data, are that diversification of types and routings of communication circuits affords maximum communication dependability. In a power organization, where the utmost reliability is desired, this diversification should include the use of power-line carrier-telephone channels which have been carefully planned to realize fully the inherent reliability of carrier service.

The interconnection of individual single-frequency carrier-telephone channels is feasible and permits the extension of this type of service over a much greater area than would otherwise be possible.

Periodic analysis of telephone traffic over all communication circuits provides a basis for determining the most efficient distribution of traffic, and this results in leveling traffic peaks, thereby reducing delays in communication during these periods. Such traffic studies help to keep the loading equalized between individual circuits in order to secure the greatest return on the investment.

Performance records reveal that the general use of emergency power-supply equipment adds to the reliability of carrier-telephone service by providing power when station-service power supply has either failed or is otherwise abnormal.

The continuity of service rendered by carrier-telephone sets can be kept at a maximum by following a maintenance program which incorporates thorough inspections at regular intervals—planned to detect irregularities in advance of their developing into conditions interfering with operation, especially in the case of vacuum tubes. If routine checks are carefully made, the possibility of extended service interruptions is rather remote.

REFERENCE

1. Rating of Potential Devices and Suggested Material for a Standard. J. E. Clem, F. O. Langguth. AIEE Transactions, volume 58, 1940, December section, pages 676–80.

INSTITUTE ACTIVITIES

AIEE Officers to Be Nominated for 1943 Election

For the nomination of national officers to be voted upon in the spring of 1943, the AIEE national nominating committee will meet during the national technical meeting, New York, N. Y., January 25–29, 1943. The officers to be elected are: a president, a national treasurer, three directors, and five vice-presidents, one from each of the even-numbered geographical Districts. Fellows only are eligible for the office of president, and Members and Fellows for the offices of vice-president, director, and national treasurer.

To guide this committee in performing its constituted task, suggestions from the membership are, of course, highly desirable. To be available for the consideration of the committee, all such suggestions must be received by the secretary of the committee at Institute headquarters, not later than December 15, 1942.

In accordance with the provisions in the constitution and bylaws, as amended during 1935 and quoted in the following paragraphs, actions relative to the organization of the national nominating committee are now under way.

Constitution

28. There shall be constituted each year a national nominating committee consisting of one representative of each geographical District, elected by its executive committee, and other members chosen by and from the board of directors not exceeding in number the number of geographical Districts; all to be selected when and as provided in the bylaws. The national secretary of the Institute shall be the secretary of the national nominating committee, without voting power.

29. The executive committee of each geographical District shall act as a nominating committee of the candidate for election as vice-president of that District, or for filling a vacancy in such office for an unexpired term, whenever a vacancy occurs.

30. The national nominating committee shall receive such suggestions and proposals as any member or group of members may desire to offer, such suggestions being sent to the secretary of the committee.

The national nominating committee shall name on or before January 31 of each year, one or more candidates for president, national treasurer, and the proper number of directors, and shall include in its ticket such candidates for vice-presidents as have been named by the nominating committees of the respective geographical Districts, if received by the national nominating committee when and as provided in the bylaws; otherwise the national nominating committee shall nominate one or more candidates for vice-president(s) from the District(s) concerned.

Bylaws

SEC. 22. During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical District that by December 15 of that year the executive committee of each district must select a member of that District to serve as a member of the national nominating committee and shall, by December 15, notify the secretary of the national nominating committee of the name of the member selected.

During September of each year, the secretary of the national nominating committee shall notify the chairman of the executive committee of each geographical district in which there is or will be during the year a vacancy in the office of vice-president, that by December 15 of that year a nomination for a vice-president from that District, made by the District executive committee, must be in the hands of the secretary of the national nominating committee.

Between October 1 and December 15 of each year, the board of directors shall choose 5 of its members to serve on the national nominating committee and shall notify the secretary of that committee of the names so selected, and shall also notify the 5 members selected.

The secretary of the national nominating committee shall give the 15 members so selected not less than 10 days' notice of the first meeting of the committee, which shall be held not later than January 31. At this meeting, the committee shall elect a chairman and shall proceed to make up a ticket of nominees for the offices to be filled at the next election. All suggestions to be considered by the national nominating committee must be received by the secretary of the committee by December 15. The nominations as made by the national nominating committee shall be published in the March issue of *Electrical Engineering* (Journal of AIEE), or otherwise mailed to the Institute membership not later than the first week in March.

INDEPENDENT NOMINATIONS

Independent nominations may be made in accordance with provisions in article VI, section 31, of the constitution and section 23 of the bylaws, which are quoted below:

Constitution

31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the bylaws; such petitions for the nomination of vice-presidents shall be designed only by members within the District concerned.

Bylaws

SEC. 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with article VI, section 31 (constitution), must be received by the secretary of the national nominating committee not later than March 25 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with article VI of the constitution and sent by the national secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

(*Signed*) H. H. HENLINE,
National Secretary

November 1, 1942

Plans Under Consideration for National Technical Meeting

An AIEE national technical meeting will be held in New York, N. Y., January 25–29, 1943, with headquarters in the Engineering Societies' Building. In accordance with the wartime policies of the Institute as adopted by the board of directors (*EE, Sept. '42, p. 477*) arrangements are being made for a number of technical sessions and conferences which will aid the war effort. Several sessions will deal with the conservation of copper and other critical materials both in the central-station and industrial-distribution fields. In co-operation with the AIEE standards committee and as already announced (*EE, Oct. '42, p. 527*), "guides" or "general principles" for the selection and operation of electric equipment are in preparation by several of the technical committees. These guides will serve as a basis for discussion in the sessions and conferences. Other sessions and conferences will deal with the subjects of dim-outs and their desirability, substitute materials—plastics and mica—and substitute materials for instruments.

For the general session consideration is being given to a program of speakers on the important subject of technical man power as an aid to the war effort. It is expected that both the military and industrial phases of this subject will be presented.

AIEE President H. S. Osborne (F '21) has appointed the following members on the general committee to make plans for the national technical meeting: *chairman*, C. R. Jones (M '30); F. A. Cowan (M '29); W. S. Hill (M '30); M. D. Hooven (M '30); A. E. Knowlton (F '30); R. L. Webb (M '35); C. C. Whipple (M '26); C. S. Purnell (M '35).

IEE Offers Facilities to US Electrical Engineers in Britain

The Institution of Electrical Engineers, London, England, in an effort to be of service to members of technical units of allied military forces in Great Britain has announced that its professional facilities, already at the disposal of Canadian and Polish engineers, are being made available to electrical engineers in the United States Army stationed in England. Although in the past there has been a mutual exchange of membership privileges between the IEE and the American Institute of Electrical Engineers, the IEE is now extending its hospitality to all members of the electrical engineering profession serving in the United States Army in Britain, according to an invitation issued by President N. Ashbridge of the IEE to General Dwight D. Eisen-

Future AIEE Meetings

National Technical Meeting
New York, N. Y., January 25–29, 1943

District Technical Meeting
Providence, R. I., April 7–9, 1943

District Technical Meeting
Kansas City, Mo., April 28–30, 1943

National Technical Meeting
Cleveland, Ohio, June 21–25, 1943

hower, commanding general of the United States Army in Great Britain. Through this invitation, use of the Institution's reference library and attendance at evening meetings will be possible for electrical engineers who wish to maintain some contact with their profession during their stay in England.

PERSONAL ....

W. R. Whitney

F. A. Lewis

C. A. Powel

Willis Rodney Whitney (A'01) vice-president in general charge of research, General Electric Company, Schenectady, N. Y., has been awarded the John Fritz Medal for 1943 (*p. 582, this issue*). Doctor Whitney was born in Jamestown, N. Y., on August 22, 1868. He was graduated from Massachusetts Institute of Technology with the degree of bachelor of science (1890), and from the University of Leipzig with the degree of doctor of philosophy (1896). He has also received the honorary degrees of doctor of science from Union College (1919) Syracuse University (1925), University of Michigan (1927), University of Rochester (1932); doctor of chemistry, University of Pittsburgh (1919); and doctor of laws, Lehigh University(1929). Since his graduation from Massachusetts Institute of Technology he has held the following positions at that institution: assistant instructor, general chemistry (1890–92), analytical chemistry (1892–94), sanitary chemistry (1896–98); instructor, theoretical chemistry and proximate analysis (1898–1901); assistant professor, theoretical chemistry (1901–04); nonresident associate professor, theoretical chemistry (1904–08); and nonresident professor of chemical research since 1908. In 1900 when the research laboratories of General Electric Company were established at Schenectady, N. Y., Doctor Whitney was appointed director of research. He became vice-president of the company and director of research in 1928, and upon his retirement in 1932 he was appointed vice-president in general charge of research. The Willard Gibbs Medal was bestowed upon Doctor Whitney in 1916, the Chandler Medal in 1920, the Perkin Medal in 1921, the gold medal of the National Institute of Social Sciences in 1928, and the Franklin Medal in 1931. He was awarded the AIEE Edison Medal in 1935, the distinguished service gold key of the American College of Physical Therapy in 1935, and the Marcellus Hartley Award of the National Academy of Sciences in 1938, and was named Chevalier of the Legion of Honor in 1937. Doctor Whitney is also a member of the American Chemical Society (president, 1909), American Society of Chemical Engineers, American Electrochemical Society (president, 1912), American Institute of Mining and Metallurgical Engineers, American Physical Society, American Association for the Advancement of Science, American Philosophical Society, American Academy of Arts and Sciences, National Academy of Sciences, and the National Research Council. He is also the author of a number of technical papers.

F. A. Lewis (A '31, M '35) associate editor of *Electrical Engineering* since 1936, has been designated to serve as acting editor for the duration of the editor's wartime leave of absence (*EE, Oct. '42, p. 528*). Born in Carverton, Luzerne County, Pa., on January 20, 1903, he was graduated from Syracuse University in 1926 with the degree of electrical engineer. His professional career includes engineering service in electric power, communications, and education. Mr. Lewis began his career in electrical engineering when, as a senior student in the summer of 1925 he was engaged in transmission and substation maintenance work for the Pennsylvania Power and Light Company, Wilkes-Barre. In 1926 he became associated with the New York (N. Y.) Edison Company, first serving in the test department (1926–29); during this period he was in responsible charge of special laboratory and field investigations pertaining to electrolysis problems, special distribution-system surveys and studies, and investigations of radio interference including the development of related special equipment. He also participated in the experimental development of carrier-current control devices for certain power-system equipment. In the transmission and distribution department (1929–30) he was engaged in the investigation of duct overheating and cable failure caused by the proximity or leakage of underground steam mains. Mr. Lewis was engaged in communications work during 1930–31 as a member of the technical staff of the Bell Telephone Laboratories, Inc., New York, N. Y. There he was engaged in ferromagnetic research, particularly with respect to the determination of the magnetic properties and behavior of certain special alloys under different conditions and as affected by various heat treatments. Some of this work involved the development of special methods of obtaining the required data. Mr. Lewis's activities in the field of technical education began while he was an undergraduate. While a junior and senior student he served as instructor in mechanical drawing at Syracuse University. From 1928 to 1931 he taught industrial mathematics in the evening school at Pratt Institute, Brooklyn, N. Y. Mr. Lewis joined the AIEE editorial staff in 1931 as assistant editor. He is also a member of Tau Beta Pi and Pi Mu Epsilon.

C. A. Powel (M '20, F '41) manager, headquarters engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been elected vice-president of the American Institute of Electrical Engineers, representing the Middle Eastern District (2). He will fill the unexpired term of Professor N. S. Hibshman (A '27, F '41), who resigned because of a change in district address. Mr. Powel was born in Rouen, France, on July 30, 1884, and was graduated from the Institute of Technology of Canton, Bern. From 1905 to 1911 he was associated with Brown, Boveri and Company, Baden, Switzerland, in the application engineering department, and in the latter year was sent to Japan as the company's resident technical engineer. He returned to England in 1915 to join the civil branch of the ordnance department and from 1916 to 1918 was engaged in ordnance work in the United States representing the British War Office. In 1919 he joined the central-station engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. He became manager, central-station engineering department, in 1935; manager, industry engineering department, in 1938; and was appointed to his present position in 1940. He became a naturalized citizen of the United States in 1930. He is a past director (1936–40) of the Institute. He was also a member of the AIEE Lamme Medal committee (1939–42), and the committees on power generation (1933–38), applications to marine work (1936–40), electric welding (1937–41), and electrochemistry and electrometallurgy (1939–40). He has served on the standards committee since 1939, the Charles LeGeyt Fortescue Fellowship committee since 1939 (chairman, 1939–41), and the committee on constitution and by-laws since 1940. He is currently serving on the committee on education. He is also a member of The American Society of Mechanical Engineers and an associate member of the Institute of Electrical Engineers, England.

Gerard Swope (A '99, F '22) honorary president, General Electric Company, New York, N. Y., has been awarded the fourth triennial Hoover Gold Medal. Details of the award are given on page 582 in this

issue. He was born on December 1, 1872, at St. Louis, Mo., received the degree of bachelor of science in electrical engineering from Massachusetts Institute of Technology in 1895, and has received the honorary degrees of doctor of science from Rutgers University (1923), Union College (1924), Washington University (1932); doctor of laws, Colgate University (1927); and doctor of engineering, Stevens Institute of Technology (1929). His first engineering experience was as a helper at General Electric Company, Chicago, Ill., in 1893. In 1895 he was employed by Western Electric Company, Chicago, Ill., as a design engineer, becoming manager of the St. Louis, Mo., office in 1899. In 1906 he returned to Chicago as general manager of power apparatus engineering department, and in 1908 he went to New York, N. Y., as general sales manager, becoming vice-president and director of the company in 1913. During World War I he was a member of the general staff of the United States Army. In 1919 he was made president of International General Electric Company, New York, N. Y., and was in charge of the companies abroad engaged in manufacturing, engineering, and commercial activities. He became president of the General Electric Company in 1922, and since 1927 has been chairman of the board of International General Electric. He was decorated by the Emperor of Japan with the Order of the Rising Sun (1917), was named Chevalier of the Legion of Honor by the French Government, and was awarded the United States Army Distinguished Service Medal, and the gold medal of the National Institute of Social Sciences (1932). He has been a member and chairman of various national and foreign technical and public service committees, including the AIEE committee on the Iwadare Foundation (1931–35). He is also an honorary member of Tau Beta Pi. He is the author of various technical papers and articles and the holder of several patents.

S. P. MacFadden (A '19, M '30) vice-president in charge of operations, Puget Sound Power and Light Company, Seattle, Wash., has been elected executive vice-president. He has been with the company since 1930. He was born June 17, 1894, in Laredo, Tex., and received the degree of bachelor of science in electrical engineering from Texas Agricultural and Mechanical College in 1916. In that year he joined Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., as a student engineer, and in 1917 he entered the distribution department, Eastern Texas Electric Company, Beaumont. After serving in the United States Army, he returned to Eastern Texas Electric Company in 1919, serving successively as assistant manager until 1925 in the Beaumont and Port Arthur, Tex., offices, and as assistant to the manager of the Southwestern district of Stone and Webster, Inc., Houston, Tex. From 1925 to 1929 he served first as manager and later vice-president of Western Public Service Company, and Missouri Service Company, Scottsbluff, Neb., and its predecessors. In 1930, after a short period with Stone and Webster Service Corporation, Boston, Mass., he was appointed vice-president, Puget Sound Power and Light Company. **C. P. Terrell** (A '10, M '18) operating manager, has been appointed vice-president of the company. Born May 1, 1885, at Jerseyville, Ill., he was graduated from University of Washington in 1910 with the degree of bachelor of science in electrical engineering. He was first employed by the Seattle (Wash.) Electric Company, one of the predecessors of Puget Sound Power and Light Company, in 1903, advancing from substation operator to superintendent of light and power of the latter's northwestern division, Bellingham, Wash., in 1922. In 1924 he left the company to become successively an executive for El Paso (Tex.) Electric Company, Tampa (Fla.) Electric Company, and Gulf States Utilities Company, Beaumont, Tex. He returned to the Puget Sound Power and Light Company in 1940 as operating manager in charge of the central-station division and the system's generation, transmission, and distribution.

J. H. Lampe (A '20, M '26) dean of engineering, professor of electrical engineering, and head of the electrical-engineering department, University of Connecticut, Storrs, has been appointed chairman of the AIEE technical committee on electric welding for 1942–43. He has served on that committee since 1939. He was born December 1, 1896, in Baltimore, Md., and was graduated from Johns Hopkins University with the degrees of bachelor of science in engineering (1918), master of electrical engineering (1925), and doctor of electrical engineering (1931). From 1918 to 1919 he served with the United States Army, and then entered the laboratory division of Winchester Repeating Arms Company, New Haven, Conn., as research engineer. In 1920 he returned to Johns Hopkins University, first as instructor in electrical engineering, then assistant professor, and finally, associate professor. In 1938 he went to the University of Connecticut as professor and head of the electrical engineering department, and in 1940 was made dean of the school of engineering. He has served in various capacities for short periods with Consolidated Gas Electric Light and Power Company, Baltimore, Md.; Chesapeake and Potomac Telephone Company, Washington, D. C.; Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; and General Electric Company, Schenectady, N. Y. He was secretary of the AIEE Baltimore Section (1933–37), and a member of the membership committee (1933–34). He is currently serving on the technical program committee, and is a member of the executive committee of the Connecticut Section. He is also a member of the American Society for Testing Materials, the Society for the Promotion of Engineering Education, Tau Beta Pi, and Sigma Xi, and is the author of several technical articles.

F. F. Ambuhl (A '17, M '26) assistant to the chief engineer, Toronto (Ont.) Hydro-Electric System, has been appointed chairman of the AIEE technical committee on automatic stations for 1942–43. He has served on that committee continuously since 1930. He was born January 25, 1886, in Farina, Ill., and received his early engineering experience with Ford, Bacon and Davis, Engineers, Birmingham, Ala., in electrical construction work. In 1908 he entered the employ of Westinghouse Electric and Manufacturing Company, Langdale, Ala., where he was engaged in the installation and operation of a five-unit hydroelectric plant. During 1910–11 he was associated briefly with the Macon (Ga.) Railway and Light Company as superintendent of construction, and with J. C. White Corporation, Atlanta, Ga., in overhead rehabilitation construction. From 1911 to 1912 he was again affiliated with Westinghouse company as erecting engineer, first near Atlanta, Ga., and later in Charlotte, N. C. In 1912 he left that company to become resident electrical engineer for Big Dome Gold Mines, Ontario, where he served until 1913. From 1913 to 1917 he was assistant engineer of stations, Toronto (Ont.) Hydro-Electric System, and from 1917–19 was general manager and chief engineer, National Abrasive Company, Hamilton and Niagara Falls, Ont. When the plant closed shortly after the end of the World War I he rejoined the Toronto Hydro-Electric System, and he has served since 1920 in his present position. He is a past chairman of the Toronto

J. H. Lampe

Gerard Swope

F. F. Ambuhl

R. G. Warner

A. G. Oehler

F. E. Harrell

J. H. Pilkington

Section (1929–30), and is currently a member of the technical program and standards committees.

J. H. Pilkington (A '26, M '34) division engineer, system engineering department, Consolidated Edison Company of New York, Inc., has been appointed chairman of the AIEE membership committee for 1942–43. He has served on that committee since 1939. He was born February 20, 1898, in Highmore, S. D., and received the degree of bachelor of science in electrical engineering in 1922 from the University of Michigan. He immediately entered the design school course of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and in 1923 was transferred to the power section of the transformer engineering department. Later in the year he joined Brooklyn (N. Y.) Edison Company, Inc., as technical assistant to the outside plant engineer, and, except for a short period during 1924 when he was employed as sales engineer for Pittsburgh Transformer Company, New York, N. Y., he has been associated since with the Consolidated Edison System. From 1924 to 1936 he was with Brooklyn Edison company, serving successively as technical assistant to the outside plant engineer; assistant engineer, outside plant bureau of the electrical-engineering department; assistant supervisor, cable bureau of the purchasing department; department assistant, purchasing department; and division engineer, commercial engineering bureau of the sales department. In 1936 he was transferred to Consolidated Edison company, where he served first as manager of the technical bureau, and more recently, as division engineer, system engineering department. He is an associate member of Sigma Xi and a member of Tau Beta Pi.

A. G. Oehler (A '18, F '26) editor, *Railway Electrical Engineer;* electrical editor, *Railway Age;* Simmons-Boardman Publishing Corporation, New York, N. Y., has been appointed chairman of the AIEE technical committee on land transportation for 1942–43. He has been a member of this committee since 1941. Born November 12, 1888, at Lake Mills, Wis., he received the degree of bachelor of science in electrical engineering (1911) from the University of Wisconsin. From 1911 to 1913 he was employed in the testing department of General Electric Company, Schenectady, N. Y., and from 1913 to 1915 he was associated with Northern Pacific Railway Company, St. Paul, Minn., in electrical construction work. In 1915 he was appointed general foreman electrician for Wisconsin Minnesota Light and Power Company, Eau Claire, Wis., and in 1917 he resigned to become associate editor of *Railway Age* and *Railway Electrical Engineer*. He has been with the Simmons-Boardman company since 1917, with the exception of a brief period during 1918–19 when he was on leave as ensign in the United States Naval Reserve. He became managing editor of *Railway Electrical Engineer* (1918), associate editor of *Railway Age* (1919), and was appointed to his present position in 1920. Mr. Oehler is a past president of the American Welding Society. He was chairman of the AIEE New York Section (1936–37) and a member of the board of examiners (1937–42). He has served on the publication committee since 1937, and is currently a member of the standards and technical program committees.

R. G. Warner (A '19, M '20) engineering department, United Illuminating Company, New Haven, Conn., has been appointed chairman of the AIEE national committee on Student Branches for 1942–43. He has served on that committee since 1940. Born November 18, 1892, at New Haven, Conn., he received the degrees of bachelor of philosophy (1914) and electrical engineer (1920) from Yale University. From 1914 to 1916 he was with Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in the student course and later as switchboard engineer. He became instructor in the department of electrical engineering at Yale University, New Haven, Conn., in 1916, and continued in that department as instructor and assistant professor until 1939, when he was appointed engineer in charge of special work for the United Illuminating Company, New Haven, Conn. In addition to his affiliation with that company he was also electrical engineer for the Connecticut Public Utilities Commission (1930–39), and has been consulting engineer for various companies. He was chairman of the AIEE Connecticut Section (1931–32), and served on the education (1924–25) and standards (1937–39) committees, and the committee on electrical machinery (1931–33). He is currently serving as a director of the Institute, and is a member of the executive committee and the committee on domestic and commercial applications. He is also a member of the Society for the Promotion of Engineering Education, Tau Beta Pi, and Sigma Xi.

F. E. Harrell (A '26, F '40) assistant chief engineer, Reliance Electric and Engineering Company, Cleveland, Ohio, has been appointed chairman of the AIEE committee on electrical machinery for 1942–43. He has served as a member of this committee since 1936. Born October 29, 1903, in Logansport, Ind., he was graduated from Purdue University with the degrees of bachelor of science in electrical engineering (1924) and electrical engineer (1929). Following a short period in the student course of Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., he joined the Reliance Electric and Engineering Company in 1924 as sales engineer in the Chicago, Ill., office. In 1927 he was transferred as design engineer to the Cleveland office, where he has worked continuously since that date. He was appointed successively engineer in charge of mechanical design (1929), engineer in charge of a-c design (1932), and assistant chief engineer (1934). He was chairman of the Cleveland Section (1937–38), and a member of the committee on applications to iron and steel production (1934–38). He has also served on the committee on industrial power applications since 1938, and is currently serving on the standards and technical program committees. He is a civil member of the American Society of Naval Engineers.

Louis Casper (M '23) recently retired general inspector, general traffic department, Western Union Telegraph Company, New York, N. Y., has become patent counsel for a number of corporations. He is associated with Leo Mandelstam, New York, N. Y. He was born June 15, 1871, in Manchester,

England, and has served the Western Union company at various times and in various capacities since 1886, when he first joined the company in the automatic repair shop, New York, N. Y. Following his apprenticeship there (1886–90) and early work as repeater and wire chief, Cheyenne, Wyo. (1890–93), he spent three years specializing in small isolated and municipal electric power plants before returning in 1896 to Western Union. During this period of association (1896–1906) he patented a printing telegraph system and several electrical devices. From 1906 to 1908 he was employed by the Sandwich Electric Company, first in the laboratory development of composite telephone and telegraph equipment and later as contracting engineer. Another year with Western Union in automatic telegraph work and as instrument and cable inspector preceded his appointment in 1909 as principal, department of telephone and telegraph engineering, Port Arthur (Tex.) Collegiate Institute. From 1911 to 1914 he was superintendent of equipment, Gulf division, Western Union Telegraph Company, Dallas, Tex., and in the latter year was appointed general inspector in New York, N. Y.

M. F. Skinker (A '22, F '34) formerly associate director of research, technical development and research department, Consolidated Edison Company of New York, Inc., has recently been appointed chief development engineer, selenium rectifier division, International Telephone and Radio Manufacturing Company, East Newark, N. J. He had been affiliated with the Consolidated Edison System since 1924, when he joined Brooklyn (N. Y.) Edison Company, Inc., as assistant research engineer in the electrical engineering department. He became assistant director of research in 1926, and in 1937 was transferred to Consolidated Edison Company of New York, Inc., in the same capacity. He remained in that position until his recent withdrawal from the company. He was born April 12, 1898, in Denver, Colo., and received the degrees of bachelor of science in electrical engineering (1919) and master of science in electrical physics (1921) from the University of Colorado, and doctor of philosophy in electrical physics (1924) from Oxford University, England. He was a member of the AIEE technical program committee (1938–40), and has served on the committee on electrochemistry and electrometallurgy since 1936 (chairman 1938–40), and the committee on basic sciences since 1942. He is also a member of the American Society for Testing Materials and the American Physical Society.

A. C. Monteith (A '25, M '40) manager, industry engineering department, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., has been appointed chairman of the AIEE technical committee on power generation for 1942 to 1943. He has served as a member of that committee since 1938. He was born April 10, 1902, in Brucefield, Ont., and received the degree of bachelor of science in 1923 from Queens University, Kingston, Ont. While still an undergraduate in 1922, he entered the student course, Canadian Westinghouse Company, Hamilton, Ont., and from 1923 to 1924 he was associated with Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., as engineer in the graduate student course. He has been with the Westinghouse company continuously since 1923. He became central station engineer in 1924, manager, central-station engineering department in 1938, and in 1941 was appointed to his present position. He was a member of the AIEE committee on protective devices (1940–42), and has served on the standards committee since 1941. He is currently serving on the technical program committee.

T. B. Holliday (A '41) major, United States Army Air Corps, Wright Field, Dayton, Ohio, has been appointed chairman of the AIEE technical committee on air transportation for 1942–43. He has served on that committee since 1941. Born June 18, 1906, in Frankfort, Ind., he was graduated from Purdue University with the degrees of bachelor of science in electrical engineering (1927), master of science in electrical engineering (1929), and electrical engineer (1931). From 1927 to 1929 he was assistant instructor in physics at Purdue University, Lafayette, Ind., and in 1929 he entered the engineering employ at Wright Field as a junior electrical engineer in design and testing of aircraft lighting. In 1933 he was engaged in a study of methods to reduce radio interference and later supervised the development of a-c power supply and equipment for use in aircraft. He became assistant electrical engineer in 1936, and associate engineer in 1940. He is currently serving on the AIEE technical program and standards committees.

C. V. Aggers (A '39) manager, engineering and manufacturing, Westinghouse X-Ray Company, Inc., Long Island City, N. Y., has been appointed chairman of the AIEE committee on the applications of electricity to therapeutics for 1942–43. He has served as a member of this committee since 1941. He was born September 3, 1905, in Franklin, Pa., and in 1925 entered the radio engineering department of Westinghouse Electric and Manufacturing Company, Baltimore, Md. From 1928 to 1931 he attended Westinghouse technical night school, and in 1932 was placed in charge of radio-interference problems for the entire company. Prior to his appointment as manager of engineering and manufacturing, he was connected with the engineering laboratories and standards department, East Pittsburgh, Pa. He is currently serving on the AIEE standards and technical program committees.

W. F. Ogden, Jr. (M '41) commercial engineer, Edison General Electric Appliance Company, Inc., Chicago, Ill., has been appointed chairman of the AIEE technical committee on domestic and commercial applications for 1942–43. He was born October 20, 1904, in New Orleans, La., and received the degrees of bachelor of arts (1926) and electrical engineer (1941) from Swarthmore College. In 1926 he entered the test course of General Electric Company, Schenectady, N. Y., and in 1927 was transferred to the central station engineering department. In 1928 he became associated with Georgia Power Company, serving successively in the purchasing department (1928–29), as substation engineer in the operating department (1929–30), and as general superintendent of appliance repairs (1930–36). In 1937 he joined Edison General Electric Appli-

C. V. Aggers

W. F. Ogden, Jr.

T. B. Holliday

A. C. Monteith

ance Company as commercial engineer. He is currently serving on the AIEE technical program and standards committees.

E. W. Schilling (A '29, M '33) professor and head of the department of electrical engineering, Montana State College, Bozeman, has been appointed acting dean of engineering. He joined the teaching staff of Montana State College in 1938 as professor and head of the department. He received the degree of bachelor of science in electrical engineering (1919) from the University of Illinois, and the degrees of master of science in electrical engineering (1930), doctor of philosophy (1933), and electrical engineer (1936) from Iowa State College.

F. C. Todd (A'27) formerly assistant professor of electrical engineering, mineral industries experiment station, Pennsylvania State College, State College, Pa., has joined the technical staff of Battelle Memorial Institute, Columbus, Ohio, where he has been assigned to research in industrial physics. He was graduated from Oklahoma Agricultural and Mechanical College in 1925 with the degree of bachelor of science, and holds graduate degrees from Carnegie Institute of Technology and the University of Chicago (*See EE, Sept., '42, p. 480*).

H. A. Walsh (A '30, M '31) electrical engineer, Doble Engineering Company, Medford Hillside, Mass., still remains in that position. He is not the new business manager of the El Paso (Tex.) Electric Company as was stated in the October 1942 issue of *Electrical Engineering*, page 532. The H. A. Walsh who was appointed to that position is a nonmember of the Institute.

OBITUARY ••••

H. Clyde Snook (A '05, F '20) consulting engineer, Summit, N. J., died September 23, 1942. He was born March 25, 1878, in Antwerp, Ohio, and received the degrees of bachelor of arts (1900) from Ohio Wesleyan University, master of arts (1902) from Allegheny College, and master of science (1910) from Ohio Wesleyan University. During 1900–01 he taught physics and chemistry in the high school, Soldiers' and Sailors' Orphans Home, Xenia, Ohio, and during 1901–02 he was assistant professor of chemistry, Allegheny College, Meadville, Pa. After a brief association with Queen and Company, Philadelphia, Pa. (1902–03), as salesman and electrical expert, he became president of the Roentgen Manufacturing Company, Philadelphia, Pa., and was in charge of technical development and manufacturing. He served in this capacity until 1913, when he became president of that company's successor, the Snook-Roentgen Manufacturing Company. From 1916 to 1917 he was vice-president of the Victor Electric Corporation, Chicago, Ill., and in the latter year he became electrical engineer with Western Electric Company, New York, N. Y. From 1925 to 1927 he served with the Bell Telephone Laboratories, and since 1927 had been a consulting engineer. He was a past chairman (1911–12) of the Philadelphia Section, held several United States and foreign patents, and was the author of various technical articles and papers. He was honored three times for his experimental work; having received the Edward Longstreth medal of the Franklin Institute, the gold medal of the Radiological Society of North America, and the gold medal of the American College of Radiology.

James Preston Edwards (A '92, M '13) retired traffic superintendent, eastern division, Western Union Telegraph Company, New York, N. Y., died July 10, 1942. He was born July 31, 1868, in Saluda County, S. C., and was graduated from Richmond Military Academy, Atlanta, Ga., in 1880. His early engineering work consisted of shop experience, installation of isolated industrial lighting plants, power surveys, and erection of telegraph power plants and wiring. From 1893 to 1896 he was associated with National Electric Manufacturing Company, Eau Claire, Wis., in power and lighting work. From 1896 to 1910 he was telegraph engineer in southern territory for Postal Telegraph Company, becoming division electrical engineer in 1905. In 1910 he joined the engineering staff of Western Union Telegraph Company, New York, N. Y., in the office of the engineer of equipment, and during 1911–12 he was traffic superintendent of the southern division, Atlanta, Ga. In 1914 he was appointed to a similar position in the metropolitan district, and in 1916 he was transferred as traffic superintendent of the western division, Chicago, Ill. In 1919 he was appointed to the staff of the vice-president in charge of traffic, New York, N. Y., and in 1921 he was appointed traffic superintendent to the eastern division, a position he held until his retirement in 1932.

John Elliott Brown (A '03) retired general manager, Ottawa Hydro-Electric Commission, died August 23, 1942. Born April 19, 1869, in Charlottetown, Prince Edward Island, he was engaged in the electrical engineering profession for 50 years. Following a short period in the testing department of the Prince Edward Island Electric Company in 1887, he joined the Royal Electric Company, Montreal, Que., in the testing and electrical construction division. In 1890 he became associated with Thompson Houston Electric Company, Lynn, Mass., and later in the year returned to Charlottetown to install an a-c plant for the Prince Edward Island Electric Company. In that same year he became electrical engineer for Standard Electric Company, Ltd., Ottawa, Ont. During his association with this company (1890–95) he designed and laid out their complete electrical works. From 1895–96 he worked for the Deschene (Que.) Electric Company, installing an a-c plant, and in 1896 he was appointed electrical engineer in charge of design and construction work. He remained with the company until 1901, ultimately becoming superintendent, and in 1901 he transferred to Consumers Electric Company, Ottawa, Ont. He continued with that company and its successor, the Ottawa Hydro-Electric Commission, until his retirement in 1937.

Edward Louis Glander (A '11) maintenance engineer, Southwestern Bell Telephone Company, Dallas, Tex., died September 10, 1942. He was born March 21, 1881, in Milwaukee, Wis., and first entered the electrical field in 1900 in the employ of Northwestern Telephone Company, St. Paul, Minn. From 1900 to 1906 he served in the installing department of that company, and from 1907 to 1908 he was superintendent, Chippewa Valley Telephone Company, Bruce, Wis. In 1909 he became associated with the Northern Pacific Railway Company, St. Paul and Staples, Minn., and later in the year was engaged in general telegraph work at Mandan, N. D. From 1910 to 1915 he was associated, first, with the Dakota Central Telephone Company, Aberdeen, and later, the Automatic Electric Company, Chicago, Ill. From 1915 to 1919 he worked for the Interstate Commerce Commission, Kansas City, Mo., and in 1919 he joined the engineering department, Southwestern Bell Telephone Company. He remained with the company continuously until his death, serving from 1921 to 1926 in the St. Louis (Mo.) office. He was also a member of the Telephone Pioneers of America.

Charles S. Zimmer (A '37) southwestern district manager, Bussman Manufacturing Company, Houston, Tex., died July 21, 1942. He was born May 22, 1891, in New Orleans, La. He entered the electrical field in 1907 as lineman and meter repairer, installer, and tester, for the New Orleans (La.) Railway and Light Company. In 1916 he became power salesman for Birmingham (Ala.) Railway Light and Power Company, and in 1916 he became high lineman with Alabama Power Company, Birmingham. After various associations with Economy Fuse and Manufacturing Company and the Fairbanks Company, New Orleans, La., he entered the employ of Bussman Manufacturing Company, St. Louis, Mo. With the exception of a three-and-one-half year association with Fairbanks Morse and Company, New Orleans, La., he had worked continuously for the Bussman company in St. Louis, Mo., and Houston, Tex., first as salesman, and finally as southwestern district manager.

Richard Lee Herpich (A '42) second lieutenant, Signal Corps Reserve of the United States Army, 425 Signal Company Aviation, Hamilton Field, Calif., died July 30, 1942. Born Sept. 12, 1920, in Pittsburgh, Pa., he was graduated from

Carnegie Institute of Technology in 1941 with the degree of bachelor of science in electrical engineering. He entered the employ of Union Switch and Signal Company, Swissvale, Pa., as student engineer in 1941. In March he left that company to accept a commission in the United States Army. He was also a member of Eta Kappa Nu.

MEMBERSHIP ..

Recommended For Transfer

The board of examiners, at its meeting on October 15, 1942, recommended the following members for transfer to the grade of membership indicated. Any objection to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Diederich, Peter, superintendent, public service department, City of Glendale, Calif.
Feiker, F. M., dean, school of engineering, The George Washington University, Washington, D. C.
Halpenny, R. H., chief engineer, California Electric Power Company, Riverside, Calif.
Henninger, G. Ross, editor, AIEE, New York, N. Y. (now on leave, serving as lieutenant colonel, Army Specialist Corps, Washington, D. C.).
Rollow, J. G., supervising engineer, Southern Calif. Gas Company, Los Angeles, Calif.

5 to grade of Fellow

To Grade of Member

Carpenter, W. P., engineer, Superior Electric Company, Bristol, Conn.
Collins, H. W., assistant to superintendent of electrical system, Detroit Edison Company, Detroit, Mich.
Fifer, Wm. H., senior electrical engineer, Bureau of Ships, Navy Department, Washington, D. C.
Flutsch, Leo, electrical design engineer, Braden Copper Company, Rancagua, Chile, S. A.
Foulon, Fred, electrical research and development engineer, Douglas Aircraft Company, Santa Monica, Calif.
Grier, L. N., electrical engineer, Aluminum Company of America, Pittsburgh, Pa.
McCoin, B. H., superintendent, Bureau Power, Knoxville Electric Power and Water Board, Knoxville, Tenn.
Meyer, R. S., chief electrical engineer, Whitman, Requardt, Smith and Kuljian Company, Denver, Colorado.
Schindler, R. W., assistant professor of electrical engineering, Fenn College, Cleveland, Ohio.
Taylor, W. H., engineer, Bureau of Reclamation, Denver, Colorado.
Toole, M. G., electrical engineer, United States Navy Yard, Charleston, S. C.
Whitford, R. A., electrical engineer, and sales manager, ReQua Electrical Supply Company, Rochester, N. Y.
Wold, E. A., automatic chief, Western Union Telegraph Company, Minneapolis, Minn.
Woodford, A. G., research department, Allen Bradley Company, Milwaukee, Wis.

14 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Names of applicants in the United States and Canada are arranged by geographical District. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before November 30, 1942, or January 31, 1943, if the applicant resides outside of the United States or Canada.

United States and Canada

1. North Eastern

Cassidy, G. E. (Associate re-election), General Electric Company, Schenectady, N. Y.
Hanfmann, A. M., Stone and Webster Engineering Company, Boston, Mass.
Harwell, H. W. (Member), Connecticut Telephone and Electric Corporation, Meriden, Conn.
McTear, C. K. (Member), Stone and Webster Engineering Corporation, Boston, Mass.
Russell, A. L. (Associate re-election), Franklin Technical Institute, Boston, Mass.
Smith, J. D., General Electric Company, West Lynn, Mass.
Symbolic, A. J., Watervliet Arsenal, Watervliet, N. Y.
Terpak, S., General Electric Company, Pittsfield, Mass.
Wentworth, C., The Acme Electric and Manufacturing Company, Cuba, N. Y.

2. Middle Eastern

Bennett, C. O., Bureau of Ships, Navy Department, Washington, D. C.
Bueno, M. deP., c/o Bureau of Inspection, Department of Labor and Industry, Harrisburg, Pa.
Caswell, A. S., I-T-E Circuit Breaker Company, Philadelphia, Pa.
Crain, C. M., Philco Corporation, Philadelphia, Pa.
Fessler, A. E., New York Shipbuilding Corporation, Camden, N. J.
Freed, L., Toledo Shipbuilding Company, Toledo, Ohio.
Gress, G. E., Automatic Temperature Control Company, Inc., Philadelphia, Pa.
Keck, C. L., Explosives Investigation Laboratory, Naval Powder Factory, Indian Head, Md.
Kleshick, F. P., New York Shipbuilding Corporation, Camden, N. J.
Lewis, D. D. (Member), Millville Manufacturing Company, Millville, N. J.
Lynott, W. J., Jr. (Member), Federal Power Commission, Washington, D. C.
May, C. W. H. (Associate re-election), Stone and Webster Engineering Corporation, Allenwood, Pa.
Moore, F. W., Bell Telephone Company of Pennsylvania, Pittsburgh, Pa.
Murphy, R. R., I-T-E Circuit Breaker Company, Philadelphia, Pa.
Roman, W. G. (Member), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Patterson, J. R., The Austin Company, Painesville, Ohio.
Pattison, D. R. (Member), Pennsylvania Electric Company, Johnstown, Pa.
Peterson, J., Westinghouse Electric and Manufacturing Company, Philadelphia, Pa.
Piper, J. F., New York Shipbuilding Corporation, Camden, N. J.
Smith, R. J. (Associate re-election), American Electrical Construction Company, Inc., Philadelphia, Pa.

3. New York City

Barrington, L. R., Brooklyn Edison Company, Brooklyn, N. Y.
Brady, P. F., Consolidated Edison Company of New York, Inc., New York, N. Y.
Coomes, H. H., Brooklyn Edison Company, Brooklyn, N. Y.
Doggett, R. J., The Foundation Company, New York, N. Y.
Gilford, E. (Associate re-election), Cox and Stevens, New York, N. Y.
Hoag, S. B. (Member), Chemical Construction Corporation, New York, N. Y.
Hochstadter, O. (Member), Lone Star Steel Corporation, New York, N. Y.
L'Allemand, C. C. (Associate re-election), General Electric Company, New York, N. Y.
Lucca, A., Brooklyn Edison Company, Brooklyn, N. Y.
Lynch, J. O. (Associate re-election), Jersey Central Power and Light Company, Morristown, N. J.
Perdiue, H. L., General Electric Company, New York, N. Y.
Ream, C. E., General Electric Company, New York, N. Y.
Reed, C. A. (Member), Board of Trasportation, New York, N. Y.

4. Southern

Bertke, L. E., United States Army, Signal Corps, Camp Murphy, Fla.
Doub, T., Florida Power and Light Company, Sarasota, Fla.
Glyptis, N. (Member), The Girdler Corporation, Louisville, Ky.
Howe, E. S. (Member re-election), Federal Power Commission, Atlanta, Ga.
Jones, W. C., General Electric Company, Richmond, Va.
Sloop, J. L., National Advisory Committee for Aeronautics, Langley Field, Va.
Vaughn, A., Wilson Dam Hydro Plant, Wilson Dam, Ala.
Woodward, E. B., Navy Yard, Charleston, S. C.
Young, R. R., General Electric Supply Corporation, Shreveport, La.

5. Great Lakes

Brem, H. C., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Copland, J. G., Tri-State College, Angola, Ind.
Fruth, H. F. (Member), Electro Manufacturing Company, Chicago, Ill.
Gancer, A. L., Oliver Farm Equipment Company, Plant #2, South Bend, Ind.
Graflan, P. S., Belmont Radio Corporation, Chicago, Ill.
Kiefert, E. E., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Learman, J. C., Studebaker Aviation, South Bend, Ind.
Morehouse, E. G., Studebaker-Aviation Division, South Bend, Ind.
Mortensen, D. S., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
Olson, B. R. (Associate re-election), Allis-Chalmers Manufacturing Company, West Allis, Wis.
Roller, J. A., Hercules Powder Company, Baraboo, Wis.
Satterfield, W. E., Ford Motor Company, Dearborn, Mich.
Swanson, A. F. H., Allis-Chalmers Manufacturing Company, Milwaukee, Wis.
York, V. O., Michigan College of Mining and Technology, Houghton, Mich.

6. North Central

Dingler, R. D., Monolith Portland Midwest Company, Laramie, Wyo.
Gaylord, E. H., Public Service Company of Colorado, Denver, Colo.
Hayami, F. Y., Engineering and Maintenance Office, Heart Mountain, Wyo.

7. South West

Abeles, M. C., City Light and Traction Company, Sedalia, Mo.
Bartels, M. W., Western Union Telegraph Company, St. Louis, Mo.
Brown, L., Missouri Electric Power Company, Marshfield, Mo.
Chaney, L. P. (Member), Lummus Company, Houston, Texas.
Cooper, E. A., Black and Veatch, Fort Smith, Ark.
Edmundson, C. W., Fluor Corporation, Kansas City, Mo.
Erskine, G. S. (Member), War Department, U. S. Engineers, Del Rio, Texas.
Fehlenberg, A. E., Union Electric Company of Missouri, St. Louis, Mo.
Lash, L. E. (Member), Fagan Electric Company, Little Rock, Ark.
McKeown, J. G., West Texas Utilities Company, Abilene, Texas.
Miller, S. L., Union Electric Company of Missouri, St. Louis, Mo.
Peake, H. S., West Texas Utilities Company, Abilene, Texas.
Schwearingen, F. L. (Member), Fischbach and Moore, Inc., Oklahoma City, Okla.
Silvus, W. E. (Associate re-election), General Electric Company, Houston, Texas.
Sutherland, D. J. (Associate re-election), Westinghouse Electric and Manufacturing Company, Houston, Texas.
Warner, W. W., Western Union Telegraph Company, St. Louis, Mo.

8. Pacific

Bloom, S. S. (Member), California Railroad Commission, San Francisco, Calif.
Jeffery, A. A., American Potash and Chemical Corporation, Trona, Calif.
Reed, W. M., Pacific Gas and Electric Company, Oakland, Calif.
Renner, J. J., U. S. Army Signal Corps, c/o Postmaster, San Francisco, Calif.

9. North West

Corfield, C. C., Puget Sound Power and Light Company, Dieringer, Wash.
Garett, L. D., Nemco Electric Company, Seattle, Wash.
Jann, J. V., General Electric Company, Portland, Ore.
Johns, S. M., Westinghouse Electric and Manufacturing Company, Salt Lake City, Utah.
Macaulay, H., Puget Sound Power and Light Company, Dieringer, Wash.
Spain, C. J., Jr., Westinghouse Electric and Manufacturing Company, Portland, Ore.
Williams, W. J. (Associate re-election), Montana Power Company, Great Falls, Mont.

10. Canada

Ackroyd, S. G., Amalgamated Electric Corporation, Ltd., Toronto, Ont.
Bent, E. D., Northern Electric Company, Ltd., Montreal, Que.
Blackmore, C. L., H. G. Acres, Niagara Falls, Ont.
Fraser, J. P. (Member), B. C. Electric Railway Company, Vancouver, B. C.
Hallrecht, A., National Research Council, Ottawa, Ont.
Yee, T. M., Defence Industries Ltd., Nobel, Ont.

Total, United States and Canada, 101

Elsewhere

Pereira, M. P. deB., Radio Cinephon Brasileira, S. A., Rio de Janeiro, Brazil, S. A.
Vanderpoll, J. A. (Member re-election), S. I. A. M. Di Tella Ltda., Buenos Aires, Argentina, S. A.

Total, elsewhere, 2

OF CURRENT INTEREST

WAR PROGRAM • •

Industry Lends 3,000 Men to Salvage Campaign

More than 3,000 trained men, loaned by private industry to assist in the industrial salvage program, will make a 90-day plant-to-plant canvass of American industry and call on the presidents of 70,000 industrial firms in the most thoroughly organized search for industrial scrap to date, according to Robert W. Wolcott, chairman of American Industries Salvage Committee.

These men will co-operate closely with the industrial salvage section of the conservation division, War Production Board, to insure that all possible dormant scrap is collected. The field force of the industrial salvage section of the WPB has been doubled to comprise 140 men to handle this drive.

The program has been organized by the industrial salvage section under Hamilton W. Wright, through the regional chiefs of the WPB, and the American Industries Salvage Committee, headed by Mr. Wolcott. Executives of these organizations, heading up this special dormant scrap drive, are:

George Ross, secretary of the salvage committee of the American Iron and Steel Institute; Walter S. Doxey, president, American Steel Warehouse Association; C. F. Winchester, executive secretary, Associated Equipment Distributors, and H. R. Doughty, director of field operations on salvage for the National Federation of Sales Executives.

Continuous production from open-hearth and electric furnaces and other users of scrap during the winter months of 1943 is dependent on the collection of 7,000,000 additional tons of iron and steel scrap prepared for delivery to the mills for use during the winter months.

Theme of the drive for dormant industrial scrap is: "If it hasn't been used for the past three months and if no one can prove it will be used in the next three—find a use for it or scrap it."

WPB Curtails Variety in Types of Electric Lamps

Types of electric lamps that may be manufactured after November 1 are reduced from 3,500 to 1,700 by a recent order of the War Production Board. This order is expected to conserve seven per cent of the critical materials previously consumed in electric lamp manufacture and to result in considerable savings in manpower, manufacturing facilities, and storage space.

There is, however, no curtailment in the total production of electric lamps allowed, and it is expected that adequate supplies of the approved types will be produced to replace those no longer made. Some types will be eliminated in all categories of incandescent, fluorescent, and glow-discharge lamps, and manufacture of parts for these lamps is also to be discontinued. Colors are restricted to red, blue, and green.

The discontinued types of lamps fall into three groups:

1. Those for which suitable substitutes are available.
2. Those for which there is no essential demand.
3. Those formerly made in a variety of different voltages and wattages, which are now so simplified that only a small number of the previously made types will be needed.

Lamps designed for diagnostic and surgical purposes and those produced for the Army, Navy, Maritime Commission, War Shipping Administration, and Lend-Lease purposes are exempt from the WPB ruling.

It is expected that 650 tons of steel, 35,000 pounds of solder, and 8,000 pounds of tungsten will be saved for more urgent war production by the new ruling. Approximately 1,300,000 man-hours of direct labor will be released for production of radio tubes and other war products, and about 325,000 square feet of floor space will be made available for production of radio tubes and other electronic devices for the Army and Navy, plus about 400,000 additional square feet in warehouse space, as a result of the order.

Dry-Cell and Flashlight Production Curtailed

Control over production of dry-cell batteries and flashlights for civilian use and restriction of raw materials used in flashlight manufacture have been ordered by the War Production Board.

Smaller plants which do not have large military orders are permitted to manufacture batteries and flashlights for civilian use at a greater rate than larger plants, which, for the most part, are operating at capacity on orders for the armed forces. Flashlights and other portable electric lanterns in the hands of manufacturers will be released primarily for industrial use, and then only for orders bearing a preference rating of A-10 or higher.

The new order prohibits the use of tinplate and terneplate in flashlight fittings, tinned copper wire for electric contacts in dry-cell batteries, iron and steel in battery outer jackets and top and bottom seals, and copper and copper base alloy except in wire and brass plating, and limits the use of zinc in dry-cell batteries.

Only 35 per cent of the number of radio batteries produced in 1941 will be manufactured, primarily for use on farms. Batteries for the portable-type radio are entirely eliminated as nonessential.

Production of flashlight batteries will be cut one half compared with 1941 output. Other types of dry-cell batteries will be reduced ten per cent, except that batteries for hearing aids and railroad lanterns will be produced in greater quantity until December 31, 1942. Output of flashlights and other types of portable electric lights will be $^1/_{10}$ of what it was in 1941.

It is estimated that about 8,000 tons of zinc will be saved for the war effort, approximately 1,000 tons of copper, and several hundred tons of steel, compared with 1940 consumption. The new order also will release much needed production facilities for military purposes.

WPB Names Committee to Plan Setup of Technical Branch

Appointment of a committee of engineers and scientists to determine the manner in which the projected Office of Technical Development should be set up within the War Production Board, and to define the scope, functions, and method of operations which the office should have, was announced today by WPB Chairman Donald M. Nelson. Decision to establish such an office was made earlier, following a report by a previous committee recommending that the War Production Board set up a strong scientific and technical organization to make sure that the nation's technical ability and resources are utilized to the full in the war-production program.

Chairman of the new committee is Webster N. Jones, director of the college of engineering, Carnegie Institute of Technology, Pittsburgh, Pa. Other members are:

Lawrence W. Bass, director of research, New England Industrial Research Foundation, Boston, Mass.; Oliver E. Buckley (F '29) president, Bell Telephone Laboratories, New York, N. Y.; Colonel Clarence E. Davies, Ordnance Department, United States Army, Washington, D. C.; Ray P. Dinsmore, manager, development department, The Goodyear Tire and Rubber Company, Akron, Ohio; Admiral J. A. Furer, United States Navy, Washington, D. C.; Jerome C. Hunsaker, head of the departments of mechanical and aeronautical engineering, Massachusetts Institute of Technology, Cambridge, Mass.; H. W. Graham, director of metallurgy and research, Jones and Laughlin Steel Corporation, Pittsburgh, Pa.; S. D. Kirkpatrick, editor *Chemical and Metallurgical Engineering*, New York, N. Y.

Silver Replaces Copper. Substitution of silver for copper in electric conductors, such as bus bars and windings for transformers, has saved 24,000,000 pounds of copper for the war program in the last few months, the War Production Board announces. A minimum of 34,000 tons of silver has been allotted to the Defense Plant Corporation by the United States Treasury and must be returned after the war. The Defense Plant Corporation is lending this silver to those

plants that must have large quantities for operation, that can conveniently protect the silver, and that are in operation almost constantly. The silver is made available with the stipulation that it can be used only for a nonconsuming purpose.

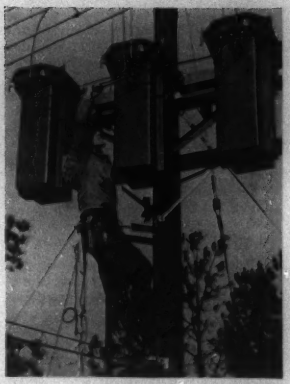
IT and T to Expand Factory Facilities. The International Telephone and Telegraph Corporation has announced plans to proceed with construction of the first unit of a new factory, which will eventually become the home of that company's research and manufacturing operations in the United States. The factory will be constructed in units following a fundamental plan which is planned to provide great flexibility for expansion. Each unit will be self-sufficient and yet will be designed so as to be co-ordinated with the other units to form an efficient and modern plant. The new unit is expected to contain about 75,000 square feet of operating space.

Electricians Trained in Quartermaster Corps

One of the chief services performed by trainees in the electricians' school of the United States Army Quartermaster Corps, Camp Lee, Va., is repair work and maintenance of electric wiring. Trainees of the school, which is conducted in 12 technical training shops, have installed the wiring in two laundry units and a mobile clothing and shoe-repair unit, have instituted the public-address units and the camp-wide broadcasting network, and set up and are now expanding the communication systems used on the post.

The school, taught by a staff of experienced noncommissioned officers, takes trainees who for the most part have had some previous experience as electricians and adapting civilian experience to Army needs, turns out the students with ratings of skilled, semiskilled, or helpers, according to their versatility as electrical technicians.

Instruction in the electricians' school is both practical and varied. Eighty per cent of the time is allotted to practical work, either experiments with the various machines in the shop, or repairing of installations about the post, as in the accompanying illustration; the remainder is devoted to lectures with emphasis placed on the practical in preference to the theoretical.



EDUCATION . . .

Stevens Institute Assumes Charge of Edison Tower

The Edison Tower at Menlo Park, N. J., erected on the site of Thomas Alva Edison's original laboratory, was placed in the keeping of Stevens Institute of Technology recently by its donor, William Slocum Barstow (F '12).

Doctor Harvey N. Davis, president of the college, headed a group of college officials making an inspection of the 131-foot structure, with its airplane beacon blacked out because of the war. The eternal light inside which was lighted by Edison himself still burns.

A bill passed by the New Jersey state legislature provided for transferring operation and maintenance of the tower and grounds from the Thomas Alva Edison Foundation, Inc. to Stevens Institute. Perpetual maintenance of the tower is guaranteed through a trust fund.

Mr. Barstow told, during a recent inspection of the tower, of how he had conceived the plan for it in 1929, while he was working with Henry Ford at Dearborn, Mich. At that time he intended it to be a temporary structure, to commemorate Edison's activities at Menlo Park from 1876 to 1886. The center of the tower was the exact location of the work bench at which the inventor had perfected the first incandescent lamp. The temporary steel tower was built and the 900 lamps in the large bulb at the top were lighted by Mr. Edison from Dearborn, Mich., on October 21, 1929, on the occasion of light's golden jubilee. In 1937 Mr. Barstow decided to replace the temporary tower with a permanent structure. "Mr. Ford urged me to construct the new tower around the temporary tower, so the new lamp could be lighted from the old, and to remove the old tower from inside the permanent tower later on," said Mr. Barstow. "In this way we hoped to preserve the light Mr. Edison had lighted, although it involved difficult methods of construction."

The permanent tower was completed and dedicated February 11, 1938, the 91st anniversary of Edison's birth. The beacon which surmounts the structure is a replica of the original incandescent lamp and when lighted, before the dimout was in effect, could be seen for many miles. The tower also contains loud speakers used as an address system, which also broadcast records of chimes and other music over a radius of two miles, in recognition of the fact that here, too, Edison invented the phonograph.

50th Anniversary of Manhattan Engineering College

A special convocation was called to commemorate the 50th anniversary of the founding of the school of engineering at Manhattan College, New York, N. Y., on October 14, 1942. In addition to the student body and alumni, the convocation was attended by dignitaries of the Catholic Church and delegates from other educational institutions and from learned societies. Honorary degrees of doctor of engineering were conferred on Commander E. H. Praeger, United States Naval Reserve, R. C. Muir (F '36) vice-president in charge of engineering, General Electric Company, Schenectady, N. Y., and F. H. Zurmuhlen, chief engineer, Walsh Construction Company, and George F. Driscoll Company. Most Reverend Francis J. Spellman, Archbishop of New York, presided.

The celebration began with an academic procession after which the Reverend Brother A. Victor, president of Manhattan College, extended the official welcome. Following his remarks, Mr. Muir delivered an address on the subject, "The Industrial Aspects of Technology—Effect Upon Economic and Social Structure With Emphasis on Present Planning and Future Readjustment." Brief remarks by Archbishop Spellman brought the ceremonies to a close, after which dinner was served to the delegates and guests.

Characterizing technology as a two-edged sword, Mr. Muir in his address declared that our superior technology will enable us to win the war, and that we must also win peace. "This will require co-ordinated planning," he continued, "in industry, in farming, in trade, in education, in the professions, in our churches, and in our government. It will require co-operation between government, industry and agriculture. . . .

"We must, I believe, have government and industry working together in full co-operation, with confidence in each other, and with full recognition of their mutual interdependence and mutual responsibilities. Barriers between groups must be removed. . . .

"If we are to obtain and maintain a long range plan to which we may work, we must have some of the ablest men in the country devoting their lives to this task. Perhaps we might have a fourth branch of government, a department of planning, or, if you prefer, of social and economic development. Its members would have the standing of justices of the Supreme Court, and its functions would be to advise the President, Congress, and the various department agencies of the government. With able men devoting their lives to the planning of the social and economic welfare of the nation, we might face the future with better hope and confidence.

"And because technological developments, particularly in the radio and the airplane, have made the world a smaller place in which to live and have brought its people closer together, we must also have some international plan of co-operation. If we are to have continuing peace throughout the world, we must have continued economic and social progress in all nations, equally, and in no nation at the expense of others. . . .

"Let us not forget that technology is not an end, but merely a means," Mr. Muir concluded. "It is man himself who is the end, and this is the true dignity of man."

"Slide Film" Aids in Teaching Fundamentals of Electricity

The ever-growing demand for more electrically trained and electrically skilled man power for the various phases of the war effort, has necessitated the creation of some method which shall serve to teach the fundamentals of electricity in the shortest possible time, because little can be done to hasten training in the more advanced and practical electrical specializations. One means of shortening the period of elementary training in electricity now being used throughout the United States by vocational and science teachers, in high schools and colleges as well as in industry, is the new "slide-film" set which consists of 12 "slide-film" productions designed to provide the beginner with an elementary knowledge of basic electricity.

By the visual medium it is believed that students get a clearer picture of the complexities of basic electricity in a much shorter time than is possible by lecture alone or by text-books alone. The films of themselves, however, are not designed to give students a complete course in the fundamentals of electricity. Rather they have been prepared to provide a broad background of principles upon which the instructor may build up to the point of specialized study.

There is a total of 837 individual pictures on the 12 filmstrips, including drawings, diagrams, photographs, graphs, and exhibits. Each individual picture carries with it, on the picture screen, explanatory text and captions which serve to aid the instructor, who may elaborate on or discuss each point as it is made visually. Each film is a separate subject, and may be shown alone or in the series. They are of the discussional type, and instructors may set the speed of projection to any pace desired.

The subjects of the 12 films available are:

1. Magnetism—the general laws and properties of magnets; magnetic effects.
2. Static electricity—the electron theory of positive and negative charges.
3. Current electricity—laws of current flow in the various types of circuits.
4. The electric cell—the change of chemical energy into electrical energy; primary and secondary cells.
5. The storage battery—the construction and use of the commercial storage battery.
6. Electromagnetism—construction and use of the electromagnet; effects of the electromagnetic field.
7. The generator—principles of the generator; types; generating direct and alternating current.
8. Alternating current—inductance, capacitance, and impedance in a circuit; transformers and rectifiers.
9. Electric motors—principles of the motor, d-c and a-c motors; universal motors.
10. Electric meters—construction and operation of various types of meters for electrical use.
11. Applications—heating and lighting.
12. Applications—solenoids, motor uses, radio, and electroplating.

All inquiries relating to these films should be addressed to the distributors, The Jam Handy Organization, 2900 East Grand Boulevard, Detroit, Mich.

HONORS

John Fritz Medal Awarded to Willis R. Whitney

Willis Rodney Whitney (A '01) chemist, engineer, inventor, author, and educator, and vice-president in charge of research, General Electric Company, Schenectady, N. Y., has been announced as the recipient of the 1943 John Fritz Medal, the highest American engineering award. Dr. Whitney has been awarded the medal "for distinguished research, both as an individual investigator and as an outstanding and inspiring administrator of pioneering enterprise, co-ordinating pure science with the service of society through industry."

First bestowed in 1902 to John Fritz of Bethlehem, Pa., pioneer iron-master and engineer in whose memory the award was established, the John Fritz Gold Medal is awarded annually for "notable scientific or industrial achievement, without restriction on account of nationality or sex." It is a joint honor, conferred by a board composed of representatives of four national societies, the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, and the American Institute of Electrical Engineers. The medal funds are administered by United Engineering Trustees, Inc., joint organization of these four societies.

Details of Doctor Whitney's professional career appear in a "Personal" item on page 574 of this issue.

Swope Awarded Hoover Medal

Gerard Swope (F '22) electrical engineer and honorary president of General Electric Company, New York, N. Y., has been announced as the recipient of the fourth triennial Hoover Gold Medal. Details of Mr. Swope's professional career are given on pages 574–5 of this issue.

The Hoover Medal was formally instituted in 1930, to commemorate the civic and humanitarian achievements of Herbert Hoover (HM '29) to whom the first award was made. The successive recipients have been Ambrose Swasey (HM '28) in 1936, and John Frank Stevens in 1939. The board of award consists of representatives of four national societies, the American Society of Civil Engineers, the American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, and the American Institute of Electrical Engineers.

OTHER SOCIETIES

AWS President Urges Less Censorship on Research

Less strict censorship of the results of scientific research was urged in the annual report of the welding research committee of the Engineering Foundation, a committee sponsored by the American Welding Society and the American Institute of Electrical Engineers. The committee's voice against censorship was raised by Colonel G. F. Jenks, president of the society during 1941–42, and chairman of the committee's industrial research division, who stated that "the division is beginning to feel the results of restrictions in the publication of information because of government censorship," and that "it believes that the greatest benefits to war production and to victory in the field will result from a liberal policy through which the results of research will be disseminated immediately to American engineers and scientists."

The committee, headed by C. A. Adams (F '13) consulting engineer, Edward G. Budd Manufacturing Company, of Philadelphia, Pa., reviewed the large number of studies on the various questions of welding, which it completed or carried on during the year ending October 1, 1942. The results of these studies were discussed at the fundamental research conference of the American Welding Society on October 12, 1942, during the society's convention in Cleveland, Ohio.

The welding research committee pointed out in its report that "more than ever, it needs the support of industry to dig a little more deeply into some fundamentals which cannot be strictly labeled immediate war needs but which, in the long run, will assist in the war effort and in peacetime activities. Dozens of instances could be cited where this support is of paramount importance." The committee has relinquished some of its activity to the federal government, and is co-operating in an advisory capacity.

The committee's literature division, headed by H. C. Critchett, "made available the best existing knowledge of European methods of welding armor plate and other alloy steels," thus enabling "our experts to take into account the best way of saving strategic alloying elements without sacrificing weldability and the necessary physical properties."

The fundamental research division, chairman of which is H. C. Boardman of Chicago, Ill., "saved at least nine months

of precious time by realizing that it would be necessary to predict the weldability of any new steel and specify the exact procedure to follow in order to get the best results. As a consequence it outlined and initiated a program of fundamental research in spite of serious financial obstacles," according to the recent statement of the committee.

The industrial research division organized new committees and adjusted activities of the existing committees in its organization to solve many problems relating to resistance welding, aircraft applications, and the subjection of welds to dynamic stresses.

ASME Elects 1943 Officers

The American Society of Mechanical Engineers recently announced its 1943 officers, who are to be installed during the society's 63d annual meeting, November 30–December 4, 1942, in New York, N. Y. The new officers are:

President: H. V. Coes, vice-president, Ford, Bacon and Davis Inc., New York, N. Y.

Vice-presidents, elected to serve a two-year term—J. W. Eshelman, president, Eshelman and Potter, Birmingham, Ala.; T. E. Purcell, general superintendent, power stations, Duquesne Light Company, Pittsburgh, Pa.; G. T. Shoemaker (F '39), vice-president, Kansas City Light and Power Company, Kansas City, Mo.; W. J. Wohlenberg, professor of mechanical engineering, Yale University, New Haven, Conn.

Managers: R. W. Morton, professor of mechanical engineering, Head of Department, University of Tennessee, Knoxville, Tenn.; A. E. White, director of engineering research, University of Michigan, Ann Arbor, Mich.; A. R. Stevenson, Jr. (F '37), staff assistant to vice-president, General Electric Company, Schenectady, N. Y.

Industrial Research Institute Meeting Held

The Industrial Research Institute held a meeting in Buffalo, N. Y., on September 4–5, with 75 industrial executives and research directors, representing member companies, and their guests attending. Principal speakers for the two day convention were Frederic Flader, chief engineer of Curtiss-Wright Corporation, Buffalo, N. Y., and C. E. K. Mees, vice-president and director of research, Eastman Kodak Company.

Papers on patent trends and pending legislation, reviewed by H. S. Demaree, head of the patent department, The Hoover Company, Chicago, Ill., and on the production requirements plan and its effect on research laboratories, outlined by E. R. Schaeffer, chief of the safety and technical equipment branch, War Production Board, Washington, D. C., were among the problems of research management discussed. The mass spectrometer as a new research tool was also described by Harold Washburn, Consolidated Engineers, Pasadena, Calif.

An inspection trip was routed through the new assembly plant of the Curtiss-Wright Corporation in Buffalo, where the group witnessed performance tests of the P-40 pursuit planes produced by this company.

The Institute, an affiliate of the National Research Council, undertakes to promote improvement of methods and more economical and effective management in industrial research through the co-operative efforts of its members. The membership is composed of 46 industrial concerns maintaining research laboratories. Their top executives in charge of research represent them in the activities of the Institute. Its headquarters are at 60 East 42nd Street, New York, N. Y., having been moved recently from Chicago, Ill.

Future Meetings of Other Societies

American Chemical Society. National Chemical Exposition and National Industrial Chemical Conference, November 17–21, 1942, Chicago, Ill.

American Institute of Chemical Engineers. 35th annual meeting, November 16–18, 1942, Cincinnati, Ohio.

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 14–18,1943, New York, N. Y.

American Physical Society. 251st meeting, November 27–28, 1942, Chicago, Ill.; 252d meeting (annual) December 28–30, 1942, New York, N. Y.; 253d meeting, December 29, 1942, Los Angeles, Calif.

American Society of Civil Engineers. Annual meeting, January 20–22, 1943, New York, N. Y.

American Society of Mechanical Engineers. Annual meeting, November 30–December 4, 1942, New York, N. Y.

Society of Naval Architects and Marine Engineers. 50th annual meeting, November 11–14, 1942, New York, N. Y.

JOINT ACTIVITIES

ECPD Adopts Resolution on Use of Engineering Man Power for War

At a meeting on September 20, 1942, in New York, N. Y., the executive committee of the Engineers' Council for Professional Development passed the following resolution relating to the distribution of engineering man power in the United States armed forces and in industry:

In modern, mechanized warfare, the need for engineers and scientists in war industries and in the fighting forces is out of all proportion to the relatively small number available, or in prospect. This is particularly true of the United States which must not only supply its own forces but serve as an arsenal for the democratic forces of the world. It is, therefore, of vital importance to the country both to conserve this talent and to distribute it where it will best serve the total war effort. Other countries have already found this necessary.

The waste of technical talent by its diversion to services where technical skill is not essential or by a failure to use the available training facilities to the full can add but little to the man power of the armed forces and may do irreparable damage; for, without adequate technical equipment and skill armies and navies are helpless.

To meet this situation, the following steps should be taken:

1. Conserve and put to most effective use existing staffs of engineers in the industries producing war materials and in the engineering schools training young men for specialized services in the armed forces and in the war industries.

Welders to Aid in War Production

These streamlined Flexarc welders in the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., mounted on wheels so as to be moved easily from place to place, are destined for shipyards, airplane plants, and other war factories.

2. Adapt all engineering, science, and management courses in colleges to the needs of war, both in the armed services and in war industries.

3. Allocate engineers to each war activity on the basis of its relative needs, considering both the armed forces and the war industries. This allocation process should provide for those who plan to study engineering, for engineering students, for engineering teachers, and for engineers of mature experience.

4. Encourage women to undertake engineering and science courses in college.

5. Continue the support of the Engineering, Science, and Management War Training program.

6. Recognize the fact that the assignment of all able-bodied engineers to the armed forces where some may be called on to render service in fields where their training will not be used is a misdirection of skill and is not in the best interest of the total war effort.

ASA Issues Letter-Symbols Standard

A new American Standard, Letter Symbols for Mechanics of Solid Bodies of 10.3-1942 has been approved and published by the American Standards Association. In addition to the 68 letter symbols approved to indicate such concepts as angular acceleration, circular frequency, factor of safety, normal strain, wave length, and the like, the new standard cites general principles of letter-symbol standardization governing manuscripts, subscripts, superscripts, unlisted magnitudes, and typography.

The new standard, available from the ASA, 29 West 39th Street, New York, N. Y., at 25 cents per copy, was prepared by the ASA sectional committee on letter symbols and abbreviations for science and engineering, under the joint technical leadership of the American Association for the Advancement of Science, the American Institute of Electrical Engineers, the American Society of Civil Engineers, the Society for the Promotion of Engineering Education, and The American Society of Mechanical Engineers.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without letter, the other lettered. Captions should be supplied for all illustrations.

Characteristics of Driven Grounds

To the Editor:

In his letter in the February 1942 issue of *Electrical Engineering*, pages 106–7, on a paper by P. L. Bellaschi, on "Impulse and 60-Cycle Characteristics of Driven Grounds," which appears in the AIEE *Transactions*, volume 60, 1941, (March section) pages 123–8, W. H. Treadway makes certain mathematical deductions relating to the response of ground electrodes to surge voltages which are based on the assumption that the ground rod is equivalent to an inductance and resistance (corresponding to the earth path) in series with an imperfect capacitor (corresponding to the contact between the metal and the soil). It has been shown by G. F. Tagg,[1] however, that this is only partially correct; the soil surrounding a rod possesses both resistance and capacitance, but these are distributed throughout the body of the soil and the equivalent circuit is rather like that of a transmission line, with the difference that whereas with the latter the resistance and capacitance per unit length are usually constant, with the ground rod the resistance and capacitance per unit distance from the rod are not constant owing to the increase of effective area through which the current flows.

Evidence for the existence of this distributed capacitance is based on extensive tests from which Tagg showed that the a-c specific impedance of a body of soil was always less than, and bore a constant relation to, the d-c specific resistance. From this relationship it is possible to relate the effective dielectric constant of soil to its specific resistance, and astonishingly high values of from 100,000 to 1,000,000 were obtained, thus confirming earlier work by R. L. Rose-Smith.[2]

Contact resistance was once thought to be the only resistance of importance with earth electrodes. O. S. Peters[3] exploded this idea but his tests on contact resistance were not quite sufficiently sensitive, and we found a few years ago, in this country, that in certain cases there did seem to be a small contact resistance. Tagg's tests, however, settled the matter and showed definitely that there was a small contact impedance which was less with alternating current than with direct current and was less at 50 than at 25 cycles per second. This impedance, in both its resistance and capacitance components, varies with the type of soil, the pressure and the nature of the surface, and material of the ground electrode, but it is of such a magnitude as to have no practical bearing on the operation of normal-sized ground rods. In some model tests on the distribution of potential around ground electrodes of various shapes, for which I was partly responsible, the contact impedance at 50 cycles per second was comparable with the total impedance and was only eliminated by making the tests at 3,500 cycles per second, but these electrodes were measured in centimeters, whereas actual ones are measured in feet, and the larger the electrode the smaller the ratio of the contact impedance to the total impedance. Tagg's results showed that for a 6-foot electrode one-inch diameter, the contact resistance is about five per cent of the total ground resistance.

Mr. Treadway is not quite correct in saying that ground rods in parallel do not follow the normal law for resistances so connected; they do if they are sufficiently far apart. Whether it is better to connect rods in parallel or drive them deeper depends entirely on the variation of soil resistivity with depth and on the nature of the soil; sometimes one method is better, sometimes the other.

There is no evidence that the resistivity of soil varies with the magnitude of the current—if we except changes due to polarization, heating, or dielectric breakdown. This was shown by C. P. Sparks as long ago as 1915, when he made tests with currents from 4 to 290 amperes.

While it is admitted that there is much yet to be learned, about ground electrodes, particularly in respect of their behaviour under surge conditions, I hardly think that the subject is in such an early stage of development as Mr. Treadway suggests, and neither do I think that any remarkable changes of practice are very likely.

REFERENCES

1. The Contact Impedance of an Earth Electrode, Part I, **G. F. Tagg.** *World Power*, volume 26, July 1936, pages 9–12; Part II, August 1936, pages 52–5.

2. Electrical Measurements on Soil With Alternating Currents, **R. L. Rose-Smith.** Institution of Electrical Engineers *Journal*, volume 75, August 1934, pages 221–37.

3. Ground Connections for Electrical Systems, **O. S. Peters.** Technological Papers, United States Bureau of Standards, publication number 108.

H. G. TAYLOR
(Electrical engineer, London, England)

Terminal Corrections for Temperature Tests on Short Samples

To the Editor:

In many temperature tests of electric wires, cables, and other equipment, the conductor and the external cooling medium are approximately uniform over the length of the sample, but the temperature at the ends differs from that at the mid-point because heat is added or extracted by the terminals. In a short sample this causes errors in the results. The following simple method can be used to correct such readings, to show that no correction is needed, or to estimate proper sample lengths.

The conductor is assumed to have constant heat input per unit length, and to have heat added or extracted at a constant rate at its terminals. Cooling is assumed to be proportional to temperature difference between conductor and surrounding medium (usually air). Temperatures along the conductor can then be represented fairly accurately by voltages along a long d-c transmission line having uniform linear resistance and shunt conductance. Heat input (or extraction) by the terminals of

the sample causes a temperature rise (or drop) which diminishes exponentially with distance from the terminal. The error in measured temperature at any point, due to end effect, can therefore be calculated if the mid-point and terminal temperatures, and the attenuation, are known. Similarly, the required length of sample to reduce the error in mid-point temperature to any desired percentage of the terminal disturbance, can be estimated.

Under the assumed conditions,

α = attenuation per inch = $\sqrt{rh}$

r is the thermal resistivity of the conductor at the test temperature, degrees centigrade per inch per watt.

h is the heat-transfer coefficient between conductor and cooling medium, watts per inch per degree centigrade temperature difference.

This can be written,

$$\alpha = \frac{I}{A}\sqrt{\frac{\rho}{k\ (\text{deg C rise})}}$$

I is the current, amperes.

A is the conductor cross-section, square inches.

ρ is the specific resistivity of the conductor material at the test temperature, ohms per inch-cube.

k is the thermal conductivity of the conductor at the test temperature, watts per degrees centigrade per inch-cube.

(deg C rise) is the average temperature rise of conductor above cooling medium.

For example, with 570 amperes in a 30-foot loop of number 3/0 copper transmission wire, measured temperatures were 133 degrees centigrade at the mid-section, 60 degrees at the terminals, 29 degrees in the air.

Then

$$\alpha = \frac{570}{0.132}\sqrt{\frac{0.70[1+0.00382(113-20)]10^{-6}}{9.7(133-29)}} = 0.135$$

Calculated temperatures along the wire therefore are

Degrees centigrade at x inches from a terminal $= 133-[133-60]\epsilon^{-0.135x}$

A comparison of calculated and measured values at several points is shown in the accompanying table.

x	Degrees C (Calculated)	Degrees C (Measured)
0	60	60
2	77	70
5	96	94
8	108	110
15	124	125
22	129	127
118	133	133

Several other experimental checks seem to show that the method is sufficiently accurate for practical purposes. If the temperature disturbance at the mid-point of a sample is to be limited to one per cent of that at the terminals, the minimum sample lengths range from about 4 feet for number 4 copper wire, to 12 feet for 75,000 circular-mils conductor. For steel wire the samples need be only 1/4 as long as for copper; if the test is made in moving air (wind velocity 5–10 mph) the above figures can be halved. For water-cooled conductors the attenuations become roughly ten times those in air, and samples can be very short.

FREDERICK BAUER (A '42)
JEROME J. TAYLOR (A '40)

(Detroit (Mich.) Edison Company)

Effect of War on Young Engineers Inducted Into Industry

To the Editor:

The many inquiries coming to me from young engineers seeking advice on their part in the war effort and the developments in United States Government policy since my talk, "The Effect of War on Young Engineers Inducted Into Industry" (*EE, June '42, pp. 281–2*), given at the AIEE North Eastern District meeting, Schenectady, N. Y., in May 1942, prompted me to write you this letter.

In the first place, it is increasingly clear to everyone that all of us in the United States are now in government service for the duration of the war. Some of us are in the armed forces and others in the industrial army that is so vital for the development and production of the highly technical material necessary in modern warfare. It is essential that a proper balance of skilled personnel be maintained in both of these armies, although the balance between them will vary with the progress of the war.

Some uncertainties have existed between the government and industrial people regarding the allocation of technical graduates to the armed forces and industry, but these are now clearing up. At least, it appears increasingly clear that highly skilled and trained people in industry must not be indiscriminately taken by the armed forces. For example, a recent letter indicates that the United States Navy has decided not to accept for enlistment any one classified as II*A*, II*B*, or III*B*, without first receiving notice from the registrant's local board that he is released for enlistment. This provision does not apply to officer candidates, however.

Young men in the industrial field should fix clearly in their minds the fact that they too are in the Army. It is quite essential that they consider classifications made by their Selective Service boards as orders from their government regarding their status. If a young man is placed in II*B*, it is very clearly an indication that he has been ordered by his government to remain in his industrial job until such time as his Selective Service board considers him for actual induction in the Army (after all of the steps that may be involved in appeals, through the State Appeal Boards, the State Directors of Occupational Deferment, and even to the Selective Service in Washington, D. C.).

Young engineers should also have a clear understanding of the operation of Selective Service, especially the results which occur when they make applications for commissions. Many a young man assumes that, as soon as he is notified to report for a physical examination, induction is inevitable, and so he takes steps to apply for a commission. He must realize, however, that a necessary part of the procedure in applying for a commission, if he is occupied in a war industry, is that he must secure a letter of release from his employer. Naturally, a letter of release to the Army or Navy for an officer's commission must be accompanied by a similar letter to his Selective Service board.

In other words, when a young man applies for a commission, his company must withdraw the request for deferment, and his local board naturally immediately places him in Class I*A*. If, then, for any reason, the applicant does not pass the rigid physical examination required for a commission, he is immediately available for induction under his I*A* classification. His employer, having once released him, cannot conscientiously again request deferment. A number of young engineers have had this experience, and have had the choice of actual induction or immediate enlistment.

There are only some 300,000 engineers in existence in the whole United States. The United States Navy alone has stated its needs during the next few years as high as 80,000 technically trained men per year. This latter number is approximately equal to the average total graduates of all the colleges of the United States in recent times. Hence, it is evident that there is an extreme shortage of technically trained people. Electrical engineers are especially in demand because of the great expansion of radio and the growing use of electrical devices by the armed services. It is, therefore, very unfortunate for us to waste technical man power by placing such men on ordinary military duty. It is exceedingly difficult, because of the large number of people involved, for the Army or Navy to identify technically trained individuals who enter service by induction, unless they are brought to the attention of the authorities by those who have good knowledge of their abilities. Men who are so identified and who are found properly qualified are normally placed in officers' training schools by the Army or the Navy, and are commissioned after a due period of training.

It is, therefore, the duty of all employers of engineers, when a young man is inducted, to call to the attention of the proper authorities in the various branches of the service the fact that he is technically trained and has certain useful experience and to suggest that he be placed in a position where his technical training can be used effectively. Not a single case of a technically trained young man coming up for induction should occur without a real effort being made to

see that the individual is properly placed. Not only employers, but also the officers of the Founder engineering societies, should be glad to help in this way.*

The advice which should be given to young men occupied in the war industries is that they should not enlist, nor apply for commissions, until their consciences clearly dictate to them that they can be more effective in the war effort in the Army or Navy than they would be in industry. They should be advised that their pride should have nothing to do with such a move. Criticisms by other people because they are not in uniform will not help the war. They should also be assured that, if and when they are inducted, every possible step will be taken to see that they are brought to the attention of the proper authorities (as officer material). They should be reminded that qualified people are normally commissioned in a very short period of time.

In other words, each man should fully inform his employer and his Selective Service board of his abilities, his experience, and his ambitions, and then accept whatever classification he is placed in. Having done this, he should put all his energies into doing the job assigned him, whether it be in the industrial army or the armed services.

M. M. BORING

(Engineering general department, General Electric Company, Schenectady, N. Y.)

* *Editor's note:* For this purpose AIEE headquarters will supply to any member upon request a statement regarding his AIEE membership, technical papers presented and published, and so forth.

Compression and Oil-Filled Cable Versus Gas-Filled Cable

To the Editor:

Having initiated the practical use of mechanical pressure for the improvement of underground power transmission, I have a few comments on the two papers, "120-Kv Compression-Type Cable" and "120-Kv High-Pressure Gas-Filled Cable," by I. T. Faucett, L. I. Komives, H. W. Collins, R. W. Atkinson, published in AIEE *Transactions*, volume 61, September section, pages 652–7 and 658–65, respectively. No impartial reader of the two papers can escape the conclusion that they do not present a fair comparison of the two types of cable. Much trouble has been taken by the authors to show that the impulse breakdown strength of the gas-filled cable is comparable to that of the compression and oil-filled types. However, this result was obtained by incorporating special features and particular precautions into the manufacture of the gas-filled cable without doing the same thing for the compression cable and then comparing the results with each other and also with the results obtained on other types of cable for which those special features and precautions have not been provided. A fair comparison, of course, can only be obtained if comparable things are compared with each other; evidently those thoroughly known features and precautions, if taken for the other types of cable would improve their performance also so that the comparison with the gas-filled type would be different and to the disadvantage of this latter type.

Then there is the question of a cable without lead sheath. European engineers do not believe in the necessity of a lead sheath, whereas engineers in the United States do. In fact we have hitherto abhorred designs for extra-high-voltage cables where the insulation is bared to the atmosphere and then pulled into a pipe to operate directly in contact with whatever may be in that pipe, for instance rust, moisture, residual air, oil or gas under pressure. With this also is connected the question of the return path for fault currents and certain unfortunate experiences both in Europe and in America when such a path was not provided for sufficiently by a lead sheath appropriately designed. I remember very well that such experiences occurred in Europe when the *H*-type cable was introduced there so that it was necessary to prove by test results that the contact between metalization and lead sheath was good enough to prevent the metalization from carrying heavy currents on a considerable distance and thereby burn.

The comparison of Figure 7 in the paper on compression cable with Figure 2 in that on gas-filled cable shows a considerably higher power factor for the gas-filled cable than for the compression cable, namely 0.5 to 0.8 as against 0.4 to 0.5, respectively. Is this perhaps accidental?

The gas-filled cable seems to have been designed for a maximum stress of about 7.3 kv per millimeter in operation as against 8.9 kv per millimeter for the compression cable. These figures have to be compared with the corresponding long time breakdown stress value of 16 kv per millimeter and 40 kv per millimeter, respectively. Therefore, the gas-filled cable has a much lower safety factor than the compression cable as both cables have been designed in this case.

From Figure 13 of the paper on gas-filled cable it may be seen that the voltage-time curve of the gas-filled cable is very much the same as that curve of a solid-type cable. The general shape of this curve in Figure 13 and also its numerical values are about the same as those well known for solid-type cable; it takes something of the magnitude of 100 hours to reach the final long-time value in both cases whereas this value is reached after very few hours (two to five) for the compression cable and also for the oil-filled cable. These similarities are certainly not accidental but they show that the mechanism of breakdown must be of the same kind for solid-type and gas-filled type on one side and different from the mechanism of breakdown of compression cable and oil-filled cable on the other side; the phenomena of ionization and deterioration which lead to the breakdown of solid-type cable must, therefore, also be present in the gas-filled cable.

With a view to what is said above, it seems justifiable to question the necessity and purpose of proposing and propagating a type of cable which in several important respects is decidedly inferior to the compression cable as, for instance, in electrical performance, heat radiation, repairs, and also, price if calculated and designed on the same basis. It is particularly interesting to ask why one should go to the complications connected with stripping off the lead sheath of a cable during installation and producing an inferior structure instead of leaving this lead sheath where it is and having a simpler installation and a better power transmission with a long time a-c breakdown strength $2^1/_2$ times higher than if the lead sheath is stripped off.

Regarding the operating record of both types we come to a similar conclusion, namely that the gas-filled cable can scarcely compete with the compression cable. This can be easily verified from the literature of the compression cable in the last ten years. By the way, it was in October just ten years ago that the first important installation of compression cable was put into service in England and this line has been working these ten years, I should say, more satisfactorily than can be expected of a first installation of such importance and of such an entirely new and revolutionary design. In this particular case a normal 33 kv cable according to the then prevailing English standards was used, put into a steel pipe and operated under pressure at 66 kv without resorting to the precautions and complications described in this paper for the manufacture of the gas-filled cable. This first compression cable in England has also gone successfully through some heavy bombing during the battle of England. I just want to put this here on record as the authors of the compression cable paper omitted to do so.

I take it that these papers on compression cable and on gas-filled cable are, in a sense, preliminary publications on a development new in the United States. I understand that the experiments on both types of cable in Detroit, Mich., are only partially completed and I hope we may look forward to further publications containing more complete and comparable data. Meanwhile, I am glad to see that this activity with new cable designs with which I have been connected in Europe since 1927 in the laboratory and since 1932 in practical construction and operation has been vigorously taken up now also in the United States and I have no doubt that this will lead to a final clarification of the most efficient and most economical design for the different practical conditions.

M. HOCHSTADTER (M '30)

(Beverly Hills, Calif.)

A Peace Worth Fighting For

To the Editor:

For several years men prominent in the profession have urged engineers to express their views on social and economic reforms in a more public manner than has been customary. Doctor Wickenden's address, "A Peace Worth Fighting For," published in the March 1942 issue of *Electrical Engineering*, pages 113–19, is an admirable example of such action. He clearly and succinctly sets forth what he believes to be

the philosophy of the war, and the reconstruction in civil life that must inevitably follow. In "Nemesis of American Business" Stuart Chase wrote ". . . the greatest need in all the bewildered world is for philosopher engineers," and that goes today with particular emphasis.

Doctor Wickenden describes some of the factors the treatment of which will condition postwar rehabilitation that will be inevitable. One view that is steadily gaining adherents he states in these words: "It is not too much to say that if civilization is not to pass into a lasting decline we in America shall have to underwrite its rehabilitation." How? He answers thus: ". . . by creating new wealth and a greater national income."

In other words we must lay the foundations for an age of plenty, and in that way achieve economic balance; that is, full production with full employment and ample buying power. In the face of dire economic conditions that seem inevitable after the war under our present capitalistic regimen, that is a large order that only radical measures will satisfy.

When the war is over there will be some seven or eight million men in the armies of Europe (not including Russia) to be demobilized. They must in some way be set to work to live, but wages will be a mere pittance, a bare subsistence. Goods to compete with American products will be marketed at a price much less than it will cost to produce them in the United States. The postwar economic problem is a most serious one. With a national debt perhaps five times that at the close of World War I, the United States Government will be in no position to extend such welfare aid as was done during the depression. The apparent alternative, to maintain production, is to reduce costs by slashing wages and profits; this, however, will invite unprecedented labor troubles that will only make the situation worse. Such a situation is a legitimate outcome of our capitalistic economy, likewise labor racketeering. But it is not inevitable if capital and labor will abandon certain iniquitous practices, and accept co-operative reorganization and rehabilitation. This is what Doctor Wickenden stressed. Economists and other far sighted men have for some time felt that such a change must come, and now we are face to face with a "must" of portentous proportions.

The type of capitalism developed in the United States during the last 60 years made the best showing of which it is capable in the 1920's, and in 1929 showed a national income of nearly $82,000,000,000. In that same year accumulated profits were $12,000,000,000 in excess of what was needed to maintain our domestic economy, and in addition there was social and economic waste amounting to about $60,000,000,000, by reason of practices incidental to our modern brand of capitalism. These two items represent in large part what was potential buying power on the basis of the business transacted. On the basis of possible economic reorganization there should have been realized out of the two items enough to have made the national income of 1929 the equivalent of $120,000,000,000.

Had 1920 economy in the United States been reorganized thus and the sums saved been applied to the low wage scale, there might have been a minimum industrial wage of $2,000. Such a reorganization now would cut production costs sufficiently to avoid serious postwar unemployment. With its economy thus rationalized, with really free initiative and free competition established, the United States would be in line to achieve economic balance and the four freedoms.

WALTER STUART KELLY (A '04)

(Consulting engineer, Brookline, Mass.)

Transmission-Line Equations

To the Editor:

The equations for the performance of uniform transmission lines are:

$$E_S = E_R A + I_R B \quad (1)^*$$

$$I_S = I_R A + E_R C \quad (2)$$

$$E_R = E_S A - I_S B \quad (3)$$

$$I_R = I_S A - E_S C \quad (4)$$

When a line is not uniform, equations (2) and (3) above become

$$I_S = I_R D + E_R C \quad (5)$$

$$E_R = E_S D - I_S B \quad (6)$$

This letter concerns the conventions involving the use of the A and D constants and the difficulties which arise when power flow is reversed. The D constant was first presented as far as the writer has been able to ascertain by R. D. Evans and H. K. Sels in their paper on "Power Limitations of Transmission Systems," AIEE *Transactions*, volume 43, 1924, pages 26–38. In that paper attention was called to the fact that if two or more nonuniform circuits were combined to obtain over-all constants, the values of A and D constants would be interchanged if the nonuniform circuits were combined in the reverse direction. However, the B and C constants would be unchanged. In this respect, the expressions, uniform and nonuniform, are loose but have come to have accepted usage. It would be more accurate to say that the line is or is not identical when viewed from opposite ends. Although the A, B, C, and D constants are functions only of the physical construction of the circuit and the frequency, the nomenclature of equations (1), (4), (5), and (6) implies that the A and D constants are functions of power flow and a recent reference book, "Electrical Transmission and Distribution Reference Book," published by the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., on the subject goes so far as to define the A constant as the open circuit voltage ratio and the D constant as the short-circuit current ratio. No mention is made in the reference book of the fact that the values of the A and D constants

* Boldface letters represent vector quantities and move as shown.

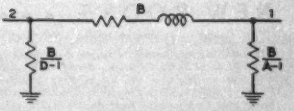


Figure 1. Equivalent Pi circuit, in terms of general circuit constants

interchange if the sending and receiving ends of the line are interchanged. According to this system, the equivalent impedance (used in impedance relay work) is always expressed as B/D with D having two values depending upon which end of the line is short circuited. For his own convenience, the writer keeps the values straight by setting up an equivalent π circuit as shown in Figure 1.

When the line is short-circuited at 1, the equivalent impedance is the parallel of B and $B/(D-1)$ which is B/D. Likewise when the line is short-circuited at 2, the equivalent impedance is B/A. This scheme, however, is inconsistent with the nomenclature of equations (1), (4), (5), and (6), and the writer hopes that this letter will start a discussion which will provide consistent expressions for the equivalent impedances and at the same time devise designations for or use of the A and D constants which will tie them into the fixed line characteristics and not into the direction of power flow. Perhaps the committee on power transmission and distribution can be persuaded to consider the case. One possible scheme would be to fix arbitrarily the order of calculating the constants according to the Evans and Sels tables and then to designate E_r as E_2 and E_s as E_1 in those tables.

The basic equations (1), (4), (5), and (6), then should be revised, and using power flows as shown by the arrows below, would be:

$$E_2 = E_1 A + I_1 B \quad (7) \qquad E_2 = E_1 A - I_1 B \quad (11)$$

$$I_2 = I_1 D + E_1 C \quad (8) \qquad I_2 = I_1 D - E_1 C \quad (12)$$

$$E_1 = E_2 D - I_2 B \quad (9) \qquad E_1 = E_2 D + I_2 B \quad (13)$$

$$I_1 = I_2 A - E_2 C \quad (10) \qquad I_1 = I_2 A + E_2 C \quad (14)$$

It will be seen that when set up in this manner, the only difference between equations (7) through (10) with respect to equations (11) through (14) in order, is in the signs of the last terms. This suggests a possible combination of these equations as follows:

$$\overset{2}{\leftarrow} \boxed{DCBA} \overset{1}{\rightarrow}$$

$$E_2 = E_1 A \mp I_1 B \quad (15)^{**}$$

$$I_2 = I_1 D \mp E_1 C \quad (16)$$

$$E_1 = E_2 D \mp I_2 B \quad (17)$$

$$I_1 = I_2 A \mp E_2 C \quad (18)$$

V. J. CISSNA (M'30)

(Power engineering and construction department, Tennessee Valley Authority, Chattanooga)

** *Note:* Signs $\mp$ or $\pm$ change with direction of power flow. When flow is from 2 to 1 the top signs are used. When flow is from 1 to 2, the bottom signs are used.

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Table of Sine and Cosine Integrals from 10 to 100. Prepared by the Federal Works Agency, Work Projects Administration for the City of New York, N. Y., conducted under the sponsorship of and for sale by the National Bureau of Standards, Washington, D. C., 1942. 185 pages, charts, etc., 11 by 8 inches, cloth, $2. (ESL).

This volume supplements the two previous volumes of sine, cosine, and exponential integrals by providing sine and cosine intergrals, calculated to ten decimal places, for the range of x between 10 and 100, at intervals of 0.01. These integrals are encountered in many branches of physics and electrical engineering, and the volume is expected to meet the needs of workers in these fields.

Mathematics of Modern Engineering, Volume 2 (Mathematical Engineering). By E. G. Keller. John Wiley and Sons, New York, N. Y.; Chapman and Hall, London, England, 1942. 309 pages, illustrations, etc., 9½ by 6 inches, cloth, $4. (ESL).

The three-volume work of which this is the second volume aims to present those aspects of mathematics which the experience of a large manufacturing organization, in dealing with mechanical and electrical investigations, has found to be of most value to engineers. This volume contains an explanation and elaboration of the fundamental method of mathematical engineering which includes the reduction of physical phenomena to a mathematical system and the solution of that system.

Electric Power Stations, volume 2. By T. H. Carr. D. Van Nostrand Company, New York, 1941. 440 pages, illustrations, etc., 9 by 5½ inches, cloth, $9. (ESL).

The aim of this two-volume English book is to provide an account of the general principles that govern the design, construction, and operation of electric power stations, which will assist the designer to choose, from the plant available, that which best fulfills the conditions to be met, and to arrange it in the most economical way. The present volume deals with the electrical equipment, station organization, and costs.

Electrical Transmission and Distribution Reference Book. By central-station engineers of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., 1942. 570 pages, illustrations, etc., 12 by 8½ inches, cloth, $5. (ESL).

This book brings together, in convenient form for reference, a large amount of practical, up-to-date information on the design and operation of transmission and distribution systems. Each chapter is by a specialist in the subject, and nearly all chapters have bibliographies. Appendixes contain tabulated statistical data on transmission lines, power systems, and transformer circuits.

Elementary Structural Analysis and Design, Steel, Timber, and Reinforced Concrete. By L. E. Grinter. Macmillan Company, New York, 1942. 383 pages, illustrations, etc., 9½ by 6 inches, cloth, $3.75. (ESL).

Intended for students of architecture and mechanical and electrical engineering and others interested in buildings and miscellaneous structures, except bridges. Although the greatest emphasis is placed on steel structures, considerable attention is given to reinforced concrete, and timber is treated adequately. Special chapters on timber-roof trusses and on column footings are included.

Marine Diesel Handbook. By L. R. Ford. Diesel Publications, New York, 1942. 896 pages, illustrations, etc., 9 by 6 inches, fabrikoid, $7; in foreign countries, $8. (ESL).

The machinery of a modern motorship is described and explained in this handbook designed for those in charge of operation and maintenance. The principles of the Diesel engine, the types in use and their construction are explained. Chapters deal with fuel, propulsion methods, Diesel-electric drives, supercharging, propellers, speed regulation, suppression of vibration and noise, electricity on the motorship, and accessory equipment.

Mathematics Dictionary. Compiled and edited by G. James and R. C. James. The Digest Press, Van Nuys, Calif., 1942. 259 pages, diagrams, etc., 9½ by 6 inches, cloth, $3. (ESL).

This dictionary is based upon modern textbooks, and aims to give the meaning of the basic mathematical words and phrases, and to cover exhaustively all terms from arithmetic through calculus, including the technical terms commonly used in the application of these subjects. Many illustrative examples and figures are included, and an appendix provides a number of useful mathematical tables.

Postwar Planning in the United States. By George B. Galloway. The Twentieth Century Fund, New York, 1942. 169 pages, paper, 60 cents.

A report of the activities of more than 100 governmental and private agencies and commercial firms throughout the country engaged in postwar planning research. The summary catalogues the leading agencies, lists and classifies the projects each has under way, and includes a bibliography of current books, pamphlets, and articles on the subject.

Condition Percent Tables for Depreciation of Unit and Group Properties (Bulletin 156). By Robley Winfrey. Iowa State College, Ames, Iowa, 1942. 177 pages, tables, paper, $3. (ESL).

Tables are assembled for the determination of annual depreciation and accrued depreciation of physical properties on the basis of age and probable life of the property units, accompanied by an explanation of their use and a description in graph and final equation form of the 18-type frequency curves.

Modern Electroplating. Electrochemical Society, New York, N. Y., 1942. 399 pages, illustrations, etc., 9½ by 6 inches, cloth, $5.50 (ESL).

Aims to provide a comprehensive survey of modern practice, prepared by various experts and provided with copious references to the literature. The opening paper describes general principles and methods. Succeeding material deals with the various metals.

PAMPHLETS • • •

The following recently issued pamphlets may be of interest to readers of "Electrical Engineering." All inquiries should be addressed to the issuers.

How Factory Accidents Happen, Descriptions of Certain Industrial Accidents, Notified to His Majesty's Inspectors of Factories. Ministers of Labor and National Service, Great Britain, November 1941. Diagrams 9½ by 6 inches, 33 pages, paper (obtainable from British Library of Information, New York, N. Y., 15 cents).

Aircraft Engine Trouble Shooting Chart. By Andrew Wallace. The Norman W. Henley Publishing Company, New York, N. Y., 1942. 22 by 32 inches, 75 cents.

Enclosed Switch Standards. National Electrical Manufacturers' Association, New York, N. Y., 1942. 19 pages, paper, 60 cents.

Power Switchgear Assemblies Standards. National Electrical Manufacturers' Association, New York, N. Y., 1942. 65 pages, paper, $3.25.

Transformer Standards. National Electrical Manufacturers' Association, New York, N. Y., 1942. 67 pages, paper, $3.

Post-War Planning. National Resources Planning Board, Washington, D. C., 1942. 32 pages, paper, 5 cents.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Any discussion of these papers will appear in the December 1942 Supplement to Electrical Engineering—Transactions Section

Practical Calculation of Circuit Transient Recovery Voltages

J. A. ADAMS, ASSOCIATE AIEE — W. F. SKEATS, MEMBER AIEE — R. C. VAN SICKLE, MEMBER AIEE — T. G. A. SILLERS, ASSOCIATE AIEE

WHILE there have been a number of papers on recovery voltage and its effect on the operation of circuit-interrupting devices, and although the transient recovery voltage and its characteristic are assuming a more important place in the design and application of circuit breakers with the growth and increasing capacity of power systems, there has not been available to the average power-company engineer a convenient method for determining this characteristic. The present paper offers such a method and also tabulates capacitance data for the more important circuit elements.

This method was developed in connection with a survey conducted by the Association of Edison Illuminating Companies to obtain a comprehensive picture of existing circuit recovery-voltage conditions. In order to review the characteristics for practically all breaker locations on the six power systems studied, it was necessary to develop a method that could be applied with minimum effort and time. The results of this survey are given in the companion paper, "Transient Recovery-Voltage Characteristics of Electric-Power Systems," by H. P. St. Clair and J. A. Adams.[1]

For different locations having the same voltage and short-circuit current duties, the transient recovery characteristic may vary with high-voltage values of approximately the same magnitude occurring over a time range of almost one hundred to one. From one end of this range to the other considerable differences may occur in the performance of some types of breaker. However, a moderate change in time to the first high peak usually produces a comparatively small change in breaker performance; a change in this time of ten to one, for instance, might produce a two-to-one change in arc length. In this situation it will be obvious that high accuracy is not required in the determination of the recovery transient, so that approximations which might be intolerable in some other applications become here quite permissible. This is very fortunate, for the circuits involved are far too complex for precise mathematical analysis and in many cases do not lend themselves well even to miniature system analysis. With a certain amount of approximation, however, these circuits may be simplified to the point where a mathematical solution is not too arduous. It is believed that the method outlined below will give results with an error of less than 20 per cent, which is considered quite reasonable. Tests have shown that in some cases much greater accuracy can be expected. Only sufficient discussion is given to explain the method of calculation and for a more complete analysis of the problem reference should be made to the various papers listed in the bibliography.

Paper 42-131, recommended by the AIEE committee on protective devices for presentation at the AIEE summer convention, Chicago, Ill., June 22-26, 1942. Manuscript submitted May 4, 1942; made available for printing May 19, 1942.

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Definitions and Basis of Calculation

The circuit recovery voltage is the voltage that appears across the contacts of a circuit-interrupting device immediately after it opens the circuit. Just before interruption the voltage across the contacts is limited to the arc voltage, and at the instant the arc is extinguished the voltage attempts to recover to the generated value. Since most short circuits are limited principally by reactance, in the usual case of a symmetrical current wave, the generated voltage is near its peak value when the circuit is interrupted at current zero and, therefore, the voltage recovery is from practically zero to peak voltage. This recovery is prevented from taking place instantaneously by the capacitance of the circuit and, because of the circuit characteristics, it may oscillate at high frequencies to nearly double its final value. Usually the capacitances involved are very small, and the recovery occurs in a matter of microseconds. For

Figure 1. Representative recovery-voltage circuit

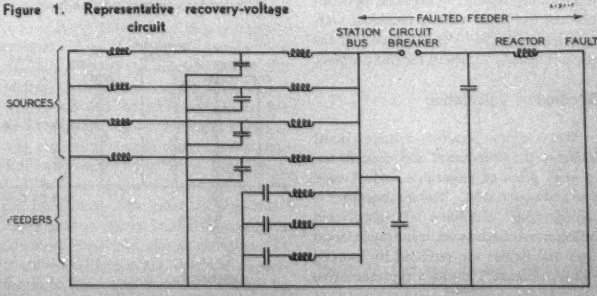


Figure 2. Simplified approximation of Figure 1

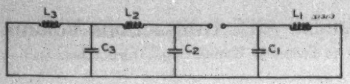


Figure 3. Simplified approximation of Figure 2

successful interruption the dielectric strength between the contacts of the interrupting device must exceed at all times the transient recovery voltage.

The method of calculation gives the *circuit* transient recovery-voltage characteristic and does not take into account any modifying action that the breaker may have on the characteristic. On an actual circuit the recovery-voltage characteristic may be modified by one or more of the following factors:

1. Asymmetry of the current wave.
2. Decay of flux in the generators during short circuit.
3. Arc voltage drop in the fault.
4. Arc voltage drop in the breaker.
5. Conduction current in the breaker after current zero.

These factors usually reduce the severity of the recovery-voltage characteristic. In order to compare calculated with test results, it is necessary to account for these factors when analyzing oscillograms obtained on test.

The calculation of the transient recovery-voltage characteristic involves the determination of the natural frequencies and voltages of the circuits affecting the recovery voltage from the inductances and capacitances of these circuits, and the combination of these values to obtain the voltage wave across the open breaker contacts. It is often not sufficient to obtain only rate of rise to the first peak, as this peak may be relatively low in comparison with some later peak which may be more important from the standpoint of breaker interrupting ability. Therefore, it is important to obtain a fairly complete voltage characteristic. The envelope over the wave is usually sufficient for this purpose.

Method of Calculation

The complete recovery-voltage circuit includes the inductance and capacitance of each piece of apparatus and of each line and connection. The mathematics is considerably simplified if distributed capacitances such as occur in transmission lines and cables are replaced by lumped values. Figure 1 shows a representative circuit resulting from this simplification. This circuit might correspond to that for a feeder breaker with a reactor on the feeder side of the breaker and a fault immediately beyond the reactor. Between the breaker and the feeder reactor is a capacitance to ground which is contributed by half of the breaker, half of the reactor, and the conductor between them.

On the bus side of the breaker is the capacitance of the bus and connected

Table I. Capacitance for Circuit 1

	Micromicrofarads
Reactor	100
Breaker and bushing	170
3 bus insulators—3×12	36
7′ of connections—7×7	49
Total capacitance	355

equipment. There are shown lumped reactances corresponding to generator, transformer, and feeder reactors. Transformers themselves are also represented here since they constitute substantially lumped reactances with a comparatively small amount of capacitance. Beyond these lumped reactances will be found the relatively large capacitances of generators, transmission lines, and cables, and, finally, completing the circuit, the additional reactances of the sources themselves.

The circuit shown in Figure 1 is too complex for convenient treatment and so

Figure 4. Station single-line diagram

*Breaker for which calculation is made

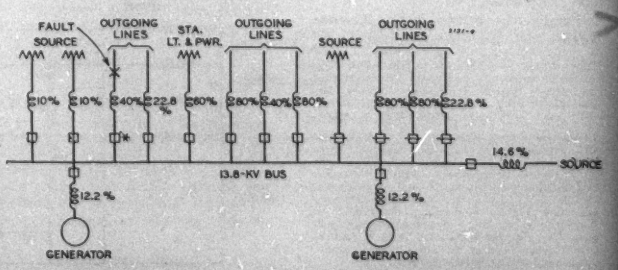


Table II. Capacitance of Circuit 3

	Microfarads
Leads to 2 transformers	2×0.584 = 1.168
2 transformers	2×0.0048 = 0.0096
2 generators	2×0.13 = 0.26
2nd bus section (similar to first)	= 0.02
4 lines	= 4.0
	5.4576 (Use 5.45)

by paralleling reactances and capacitances in the source circuit and also in the outgoing feeder circuit, it is reduced to the circuit of Figure 2. This involves an approximation which would not be permissible in very precise work but will, in general, be satisfactory for the present purpose.

In a similar manner the circuit of Figure 2 is reduced to that of Figure 3.

It is possible to go immediately from the circuit of Figure 1 to the circuit of Figure 3 by means of the following procedure.

1. Determine the parallel reactance of all reactors connected to the bus except the one on the faulted line. Use the corresponding inductance as L_3.

2. Add together all the capacitances connected on the left side of these reactors. The resulting sum is C_3.

3. Determine the inductance corresponding to the reactance limiting short-circuit current on the bus. Subtract L_3 from this inductance. The result is L_4.

The transient corresponding to each of these circuits consists of a number of oscillations of different voltages, different frequencies, and different damping factors. Each of these oscillations considered by itself starts from zero and leaves a certain voltage across the breaker when it has died down, oscillating in the meantime between zero and twice that voltage value as shown in Figure 19. Figure 11 shows a transient in which a number of these oscillations are combined. The equation for such a transient is

$$E = e_1(1-\epsilon^{-\alpha_1 t}\cos 2\pi f_1 t) + e_2(1-\epsilon^{-\alpha_2 t}\cos 2\pi f_2 t) + e_3(1-\epsilon^{-\alpha_3 t}\cos 2\pi f_3 t) + \ldots .$$

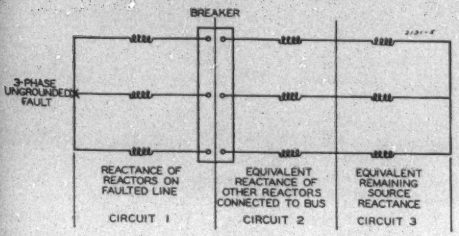


Figure 5. Reduction of system to three circuits

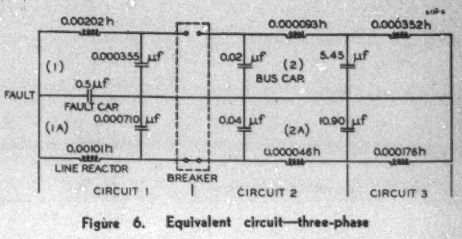


Figure 6. Equivalent circuit—three-phase

where e_1, e_2, e_3 . . . are the voltages associated with the various oscillations, f_1, f_2, f_3 . . . are the corresponding frequencies, and a_1, a_2, a_3 . . . are the respective decrement factors. Each of these oscillations may be considered to be associated with one inductance–capacitance pair (sometimes modified by the presence of the remainder of the circuit), and the voltages and frequencies are determined from the inductances and capacitances of these pairs.

Where an inductance and capacitance stand by themselves, as do L_1 and C_1 in Figure 3, the frequency associated with them is given by the well-known formula

$$f = \frac{1}{2\pi\sqrt{LC}}$$

and the voltage is equal to normal crest voltage times the ratio of the particular inductance concerned to the total inductance of the circuit. Where two adjacent circuits are coupled inductively or capacitively, however, they will react on each other, and this must be taken into account in determining frequencies and voltages. Boehne[5] has developed a method for doing this with two circuits so coupled.

Quite often with two adjacent circuits, the frequency of the first circuit is much higher than that of the second circuit, and the coupling capacitance is so high that it offers negligible impedance to current in the first circuit. In such a case fairly accurate results may be obtained by solving the two circuits independently. This is particularly helpful, where there are three or more adjacent circuits, in reducing the number to two so that Boehne's procedure can be applied.

Table III. Voltage Distribution

Circuit	Inductance	Per Cent Voltage	Volts
3A	0.000366 (L_B)	10.0	1,690
1A	0.000865 (L_S)	23.5	3,970
1	0.002020	54.5	9,210
3	0.000445	12.0	2,030
	0.003696	100.0	16,900

The decrement factors involve the resistances associated with the circuits. Since it is difficult to carry resistance values through these reductions, and fairly wide variation in decrement factor introduces comparatively small variation in the initial part of the curve, an approximate value for the decrement factor can be used for all circuits. In the survey referred to above, a factor which gave a decrement to 85 per cent of the initial value at the end of the first half-cycle was used for each oscillation. This factor gives a decrement to 20 per cent of the initial value in five cycles. This was based on observation of the decrement indicated in a number of cathode-ray oscillograms taken on actual circuit interruptions. Figure 19 shows a wave with this decrement.

This method must be considered to be a very much simplified one which will give results with reasonable accuracy in a great many cases. While it would be more accurate to consider both positive- and zero-phase-sequence values for all circuits, this will introduce additional complication which does not seem to be warranted except in special cases. Caution should be exercised, particularly where a higher degree of accuracy is desired, in simplifying circuits by the method suggested to avoid introducing unnecessary errors.

Inductances for circuits and equipment can be obtained from the reactance data used for short-circuit calculations. Capacitance data can be obtained by direct measurement when the circuit can be isolated, and when measuring equipment is available. However, if this is impractical, sufficient accuracy can be obtained by summation of the capacitances of the various circuit elements. Capacitances of equipment can be obtained from the manufacturers, the capacitances of cables and wires can be determined from standard formulas given in most handbooks, and those of copper connections in cells can be estimated by graphical methods.[8] Some data are given in the appendix for the more important circuit elements. It is extremely important that the capacitances of the higher-frequency circuits be estimated accurately, especially when the voltages associated with them are a relatively high proportion of the total voltage.

The following example illustrates the method of calculation. While there are various methods of simplification for circuits, only a few possibilities are illustrated. Various factors are brought out in the discussion of this example which have not been covered in the foregoing.

Example

This calculation obtains the transient recovery-voltage characteristic for the first phase of a breaker to open a three-phase ungrounded fault on a generating station feeder. The fault current is limited by reactors installed close to the breaker, with the result that the capacitance is low between the breaker and reactor, and the rate of rise of the transient recovery voltage for this portion of the circuit is extremely high. It will usually be found that circuits of this type give severe recovery-voltage characteristics.

The single line diagram of the station is shown in Figure 4 with breaker positions indicated and reactance values given on a

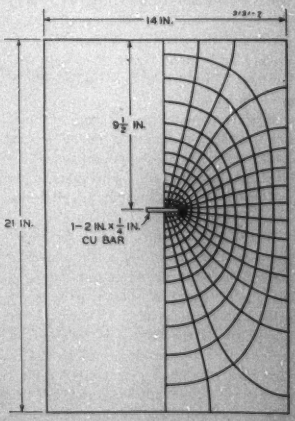


Figure 7. Flux plot for lead run in switch house

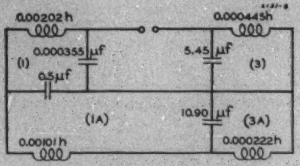


Figure 8. Equivalent circuit—reduced

100,000-kva 13,800-volt three-phase basis. In general, more severe recovery conditions are obtained when some circuits are disconnected, because this reduces the capacitance of the system. In analyzing the recovery characteristics of a system, it is advisable to consider probable operating connections for both normal and emergency conditions and to calculate the recovery characteristics for the one most likely to produce severe characteristics. This is analogous to the determination of short-circuit duty in applying circuit breakers.

The system can be reduced to three principal circuits limiting the fault current, Figure 5. These three circuits consist of:

1. A circuit from the fault to the breaker.
2. An equivalent circuit, the reactance of which is the parallel reactance of all reactors connected to the bus except the reactor on the faulted line.
3. An equivalent circuit representing the remainder of the system reactance.

The fault has been assumed to be a three-phase ungrounded short circuit, and the recovery characteristic is calculated for the first phase to clear, since this combination gives the most severe recovery-voltage characteristic. If it were considered impossible to obtain this type of fault, and, for example, only a phase to ground fault could occur, then the problem would reduce to a consideration of one phase only.

Phase-to-neutral capacitances are used for the three-phase ungrounded-neutral fault case. For most apparatus and for enclosed busses and connections these will usually be the same as phase-to-ground values.

At the time of clearing of the first pole, the second and third poles of the breaker are substantially closed circuits, and the circuit for the corresponding transient will be an outgoing circuit, consisting of the phase of the first pole to clear, in series with a return circuit consisting of the other two phases in parallel. Thus the return circuit will have just half the inductance and twice the capacitance of the outgoing circuit.

Introducing capacitances into the circuit of Figure 5 and paralleling the second and third phases, the circuit becomes that shown in Figure 6. The values of the constants are determined by the following method.

Circuit 1

The inductance will be that of the reactor in the faulted line. On the 100,000-kva 13,800-volt three-phase base, the reactance is 40 per cent, which is equivalent to an inductance of 0.00202 henry.

The capacitance will be that of the connections between the breaker and the reactor, including one end of the reactor and one half of the breaker. The capacitances of equipment are obtained from the tables in the appendix.

The capacitance of the connection was determined by means of the flux plot, Figure 7. This is a scale drawing of the conductor and the inside of the concrete cell with lines of flux and equipotential surfaces drawn in. The capacitance is calculated from the following equation:

$$C = 2.7\frac{w}{l} \text{ micromicrofarads per foot}$$

where

w = number of tubes of flux = 34

l = number of cells per tube = 13

$$C = 2.7\frac{34}{13} = 7.06 \text{ micro-microfarads per foot}$$

The total capacitance for circuit 1 is obtained by summation of the capacitances of the various parts, as shown in Table I.

Circuit 2

The reactance is equivalent to the parallel reactance of all reactors connected to the bus, except those on the faulted line. This parallel reactance is 1.83 per cent, equivalent to an inductance of 0.000093 henry.

The capacitance includes that of one half of the breaker on the faulted line, the connections from this breaker to the bus, the bus, and the connections from the bus to and including one half of the reactors. This is obtained by the method used for circuit 1 and is 0.02 microfarad.

Circuit 3

The inductance of the equivalent source reactance can be obtained by determining the equivalent system reactance for a bus short circuit and subtracting the reactance of the equivalent reactor of circuit 2.

From a short-circuit board study the bus fault current was determined to be 47,400 amperes, which is equivalent to a reactance of 8.8 per cent on a 100,000-kva 13,800-volt three-phase base. Subtracting the equivalent reactance of circuit 2

$$8.8 - 1.83 = 6.97 \text{ per cent}$$

which is equivalent to an inductance of 0.000352 henry.

The capacitance of this circuit is considered to be that from the reactors to the next large lumped reactance such as a transformer or generator. Actually in the case of a transformer there will be additional circuits beyond the transformer, but for practical purposes these usually need not be analyzed separately.

In this case the leads to the transformer banks consist of two 2,000,000 circular-mil lead-covered cables per phase which have a total capacitance of 0.584 microfarad.

The transformers are General Electric Company rated 20,000-kva 13,800–69,000-volt three-phase, and are delta-connected on the low-voltage side. From Figure 13, and the method explained in the appendix, the capacitance is 4,800 micro-microfarads.

The generators are General Electric Company, rated 75,000-kva 13,800-volt three-phase. Substituting in the equation given in the appendix:

$$C = 0.0187\frac{75}{\sqrt{13.8(1+0.08\times 13.8)}}$$

$$= 0.26 \text{ microfarad per phase}$$

One half of this capacitance is considered concentrated at the generator terminals.

The lines are 3×350,000 circular-mil cable with an average length of two miles and a capacitance of 0.5 microfarad per mile. Since the lines are short, the total capacitance is effective, which for the

Table IV. Times to First Peaks

Circuit	Microseconds
3A	162
1A	67
1	2.6
3	155

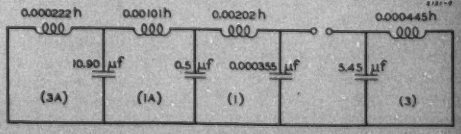


Figure 9. Equivalent circuit—rearranged

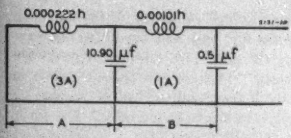


Figure 10. Circuits 1A and 3A

four lines is four microfarads. The capacitance of the station light and power section is negligible in comparison with that of the cables.

The total source capacitance is shown in Table II.

Fault Capacitance

Since the fault is ungrounded, there is a capacitance to ground at this point which consists of the three conductors of the open circuited line. Assuming the fault to be on a short line of 3,500 feet of 3×350,000 circular-mil cable, the equivalent length of line to use for obtaining the fault capacitance can be obtained from the following equation which is explained in the appendix:

$$M=\left(\frac{\pi}{4}\right)^2\frac{L}{l}$$

where

L = inductance of the return circuit = 0.001232 henry

l = 1/3 zero-phase-sequence inductance per mile of line in henries = 0.00067 henry

therefore

$$M=\left(\frac{\pi}{4}\right)^2\times\frac{0.001232}{0.00067}=1.14 \text{ miles}$$

Since M is greater than the actual length of line, the total capacitance to ground of the line is used. For 3×350,000 circular-mil cable the zero-phase-sequence capacitance is approximately one half the positive-phase-sequence capacitance,[9] or 0.25 microfarad per mile. The fault capacitance is three times the zero-phase-sequence value, or 0.5 microfarad for 3,500 feet of cable.

Equivalent-Circuit Reduction

The upper part of the equivalent circuit, Figure 6, represents the first phase of the breaker to open, and the lower part represents the other two phases in parallel. The voltage will be distributed around the circuit approximately in proportion to the inductances, and the frequencies will be determined by the inductances and capacitances.

This diagram is simplified as explained below. Some of the reductions are approximations, but it is believed that they are sufficiently accurate for practical purposes.

Table V. Recovery Voltage

Time Micro-seconds	Circuit 3A 1,600 Volts π	Circuit 3A 1,600 Volts V	Circuit 1A 3,970 Volts π	Circuit 1A 3,970 Volts V	Circuit 1 9,210 Volts π	Circuit 1 9,210 Volts V	Circuit 3 2,030 Volts π	Circuit 3 2,030 Volts V	e Volts
2.6	—	—	0.04	—	1.0	17,000	—	—	17,000
67	0.41	1,250	1.00	7,350	25.8	9,210	0.43	1,620	19,430
100	0.62	2,230	1.50	3,970	38.4	9,210	0.65	2,840	18,250
120	0.74	2,700	1.80	1,550	46.0	9,210	0.77	3,370	16,830
140	0.86	3,000	2.10	1,270	54.0	9,210	0.90	3,700	17,180
155	0.96	3,120	2.32	2,460	59.5	9,210	1.00	3,760	18,550
162	1.00	3,120	2.42	3,260	62.3	9,210	1.04	3,740	19,530
180	1.11	3,000	2.69	5,400	69.1	9,210	1.16	3,500	21,110
190	1.17	2,870	2.84	6,120	73.0	9,210	1.23	3,280	21,480

Since the voltage across circuit 2 will be small compared with that of circuits 1 and 3, the error in adding the inductance of this circuit to that of circuit 3 will be negligible. Also, the error in neglecting the capacitance of circuit 2 and the capacitance of the two paralleled phases of circuit 1 will be small. By making these changes the circuit reduces to that shown in Figure 8. Figure 9 shows this circuit rearranged in a more convenient form for analysis. Since circuit 3 is separated from the rest of the circuits by the open breaker contacts there will be no interaction between it and the other circuits, and, therefore, its frequency will be determined directly by its inductance and capacitance.

By inspection of circuits 1 and 1A, it is evident that the frequency of circuit 1 is high and also that the 0.5-microfarad capacitance of circuit 1A is large compared with the constants of circuit 1. Therefore, circuit 1 can be treated as an independent circuit. This may be proved by the following method if desired.

For two interacting circuits with similar characteristics, the voltages and frequencies can be obtained by the method developed by Boehne.[3] Applying this method to circuits 1A and 3A, shown separately in Figure 10:

$$n_0=\frac{L_B}{L_A}=\frac{0.00101}{0.000222}=4.55$$

$$m_0=\frac{C_B}{C_A}=\frac{0.5}{10.90}=0.046$$

From Figure 20

$K_S=2.3$

$$f_A=\frac{1}{2\pi\sqrt{0.000222\times10.9\times10^{-6}}}=$$

3,240 cycles per sec

$$f_B=\frac{1}{2\pi\sqrt{0.00101\times0.5\times10^{-6}}}=$$

7,100 cycles per sec

$f_S=2.3\times3,240=7,450$ cycles per sec

$$f_R=\frac{7,100}{2.3}=3,100 \text{ cycles per sec}$$

The true frequencies (f_S and f_R) for these circuits, therefore, differ five per cent from the individual circuit frequencies (f_A and f_B).

Determining the voltage distribution by Boehne's method, using the magnitude curves, Figure 21:

$J_S=3.9$

$J_R=1.65$

As a check on these values, J_S+J_R should equal n_0+1

$J_S+J_R=5.55$

$n_0+1=5.55$

$L_R=1.65\times0.000222=0.000366$ henry

$L_S=3.9\times0.000222=0.000865$ henry

These new inductances are 30 per cent and 70 per cent, respectively, of the total inductance of the two circuits compared with 17 per cent and 83 per cent for the original inductances.

These new inductances are used to

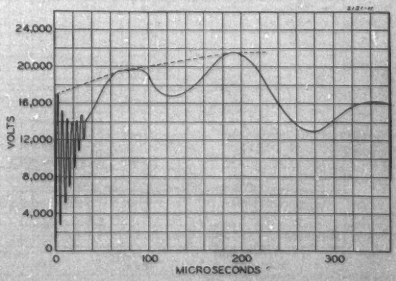


Figure 11. Recovery-voltage curve

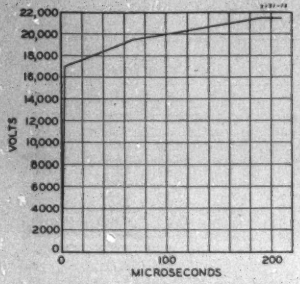


Figure 12. Envelope of recovery-voltage curve

determine the voltage distribution for circuits 1*A* and 3*A*.

Frequencies

The circuit frequencies are determined as follows:

Circuit 3*A*—3,100 cycles per second, from f_R above

Circuit 1*A*—7,450 cycles per second, from f_R above

Circuit 1

$$\frac{1}{2\pi\sqrt{0.00202\times0.000335\times10^{-6}}} = 194{,}000 \text{ cycles per sec}$$

Circuit 3

$$\frac{1}{2\pi\sqrt{0.000445\times5.45\times10^{-6}}} = 3{,}240 \text{ cycles per sec}$$

Voltage Distribution

The total voltage around the circuit for a three-phase ungrounded fault will be 1.5 times the phase-to-neutral voltage, that is, the crest value of the voltage of one phase plus the crest value of the mean of the voltages of the other two phases. For the system voltage of 13,800 volts:

$$e = 13{,}800\frac{\sqrt{2}}{\sqrt{3}}1.5 = 16{,}900 \text{ volts}$$

The voltage will be distributed in proportion to the inductances as shown in Table III.

Recovery-Voltage Equation

Substituting the voltages and frequencies in the recovery-voltage equation gives the following for the transient recovery voltage of the circuit:

$$\begin{aligned} e = {} & 1{,}690(1-\epsilon^{-a_1 t}\cos 2\pi 3{,}100t) + \\ & 3{,}970(1-\epsilon^{-a_2 t}\cos 2\pi 7{,}450t) + \\ & 9{,}210(1-\epsilon^{-a_3 t}\cos 2\pi 194{,}000t) + \\ & 2{,}030(1-\epsilon^{-a_4 t}\cos 2\pi 3{,}240t) \end{aligned}$$

First Peaks

The first peaks of each of these waves occur when

$$2\pi ft = \pi$$

therefore

$$t = \frac{10^6}{2f} \text{ microseconds}$$

For these circuits, the times to first peaks are shown in Table IV.

Recovery-Voltage Curve

The method for the determination of points on the recovery-voltage curve is illustrated in Table V. The values under the heading π are time expressed as a fraction of time to the first peak of the corresponding wave. The corresponding voltages are obtained by using these fractions as abscissae for the decrement curve, Figure 19, and multiplying the corresponding ordinates by the voltage for the circuit as given in Table III. The total voltage at any time is the sum of the voltages of the individual circuits.

The recovery-voltage curve out to the maximum peak is shown on Figure 11. The labor involved in determining this entire curve is considerable, however, and most practical purposes will be served if the envelope consisting of the curve up to the first peak and the dotted line joining the peak with subsequent peaks are shown. This requires the calculation of only a comparatively small number of points as shown in the table. The curve is shown in Figure 12.

The rate of rise of the recovery voltage may be considered to be the rate of rise to the first peak. For this example it is:

$$rr = \frac{17{,}000}{2.6} = 6{,}500 \text{ volts per microsecond}$$

Table VI. Total Capacitance to Ground of Single-Phase Core-Type Transformers

Westinghouse Electric and Manufacturing Company

	Capacitance in Micromicrofarads		
Kva	115 Kv	161 Kv	230 Kv
5,000	2,550	2,750	2,350
10,000	2,450	3,650	2,750
15,000	3,400	3,650	2,950
20,000	3,650	3,650	3,050

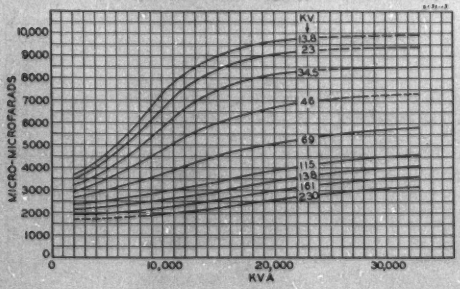
The maximum rate of rise is the slope of the line passing through zero and tangent to the first peak. This is:

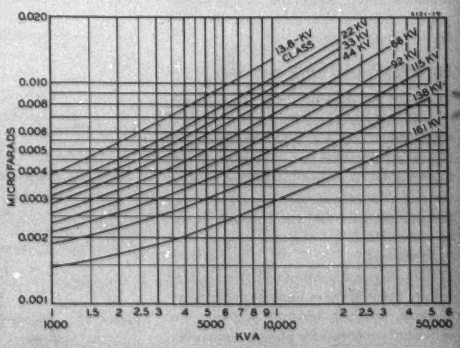
$$rr_{max} = 1.14\times6{,}500 = 7{,}400 \text{ volts per microsecond}$$

As mentioned previously, the representation and simplification of this circuit exemplifies only one of a number of general methods. The representation of distributed constants by lumped constants sometimes requires more elements than at others, depending upon the circuit in which they are located. As the accuracy of the calculation depends upon the accuracy with which the circuit is repre-

Figure 14. Capacitance of typical power transformers—high-voltage to low-voltage and ground, single-phase, 60 cycles—data from tests (Allis-Chalmers Manufacturing Company)

Figure 13. Approximate trend of capacitance to ground of windings of single-phase core-type transformers with concentric windings (General Electric Company)





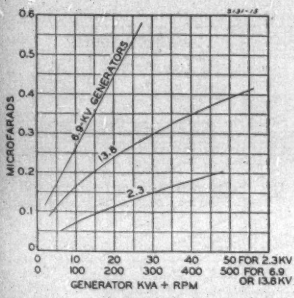


Figure 15. Effective capacitance to ground of salient pole generator stator windings—one-half capacitance of one phase to ground—all curves are the average of a large number of calculated curves (Westinghouse Electric and Manufacturing Company)

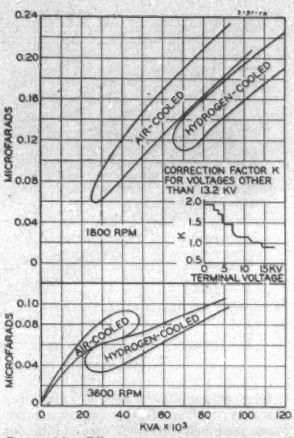


Figure 16. Effective capacitance to ground of turbine-generator windings—one-half capacitance of one phase to ground (Westinghouse Electric and Manufacturing Company)

Microfarad basis—13.2 kv; multiply capacitance by K for voltages other than 13.2 kv

sented, as well as upon the assumptions made in simplifying it, both should be carefully studied.

Appendix. Capacitance Data

The following capacitance data are based on tests or computation by the manufacturer of the equipment unless otherwise noted.

Transformer Windings

General Electric Company. For single-phase transformers with concentric windings the total winding capacitance is given in Figure 13. These curves show only approximate trends. Individual transformers may deviate considerably from them. For capacitance of windings rated less than 13.8 kv, the 13.8-kv curve will apply.

The effective capacitance concentrated at each end of the transformer winding is one half of the curve value. The capacitance should be determined using the line voltage, whether the transformers are connected wye or delta, since the capacitance depends on the insulation thickness which is determined by the operating voltage of the transformer.

For a bank of transformers connected wye, one half of the capacitance of the transformer winding, as determined from the curve, should be used when considering each phase of the system. For a bank of transformers connected delta, the capacitance per phase is equal to the value obtained from the curve, because there are two transformers connected to each line.

For three-phase transformers, the capacitance per phase is approximately one half of the value given by the curve. The transformer kilovolt-ampere capacity to apply to the curves to obtain the capacitance is the three-phase kilovolt-ampere rating of the transformer.

For Pyranol transformers, the capacitance values are 1.6 to 1.7 times the curve values.

For a more complete discussion of these curves refer to "Equivalent Circuits of Transformers and Reactors to Switching Surges."[7]

Westinghouse Electric and Manufacturing Company. Table VI gives total capacitance to ground of single-phase core-type transformers. Table VII gives total capacitance to ground of single-phase shell-type transformers. The effective capacitance concentrated at each end of the transformer winding is assumed to be one half of the total capacitance.

Allis-Chalmers Manufacturing Company. The total winding capacitance for the high-voltage windings of various sizes of transformers are shown in Figure 14. The effective capacitance concentrated on each end of the winding is assumed to be one half the total value.

Table VII. Total Capacitance to Ground of Single-Phase Shell-Type Transformers

Westinghouse Electric and Manufacturing Company

Kva	Capacitance in Micromicrofarads 115 Kv	230 Kv
10,000	5,500	5,900
20,000	7,100	7,700

Table VIII. Effective Capacitance of Potential Transformers

Westinghouse Electric and Manufacturing Company

Kv Class	Ratio	Capacitance (Micromicrofarads)
25	23,000–115	180
34.5	34,500–115	175
46	46,000–115	185
69	69,000–115	310

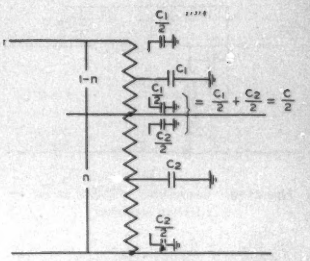


Figure 17. Capacitance distribution for autotransformers

Autotransformers

The capacitance of an autotransformer may be assumed to be distributed as shown in Figure 17.

C = total capacitance of autotransformer winding as determined from curve or tabulation (determine for transformer kilovolt-amperes, not circuit kilovolt-amperes)

n = ratio—low voltage to high voltage

$C_1 = (1-n)C$

$C_2 = nC$

Capacitance at high-voltage line end will be $C_1/2$

Capacitance at low-voltage end connected to tap will be $C/2$

Potential Transformers

Westinghouse Electric and Manufacturing Company. Effective values, that is, one half the measured winding capacitance, are shown in Table VIII.

Current Transformers

Average values for total winding capacitances are given in Table IX.

Induction Regulators

To determine the effective capacitance of induction regulators, it may be assumed that one half of each total winding capacitance is concentrated at each end of the winding as indicated in Figure 18.

C_P = total capacitance of primary winding

C_S = total capacitance of secondary winding

Table IX. Total Capacitance of Current Transformers

Kv Class	Type	Capacitance Micromicrofarads
General Electric Company		
7.5–15	Indoor	120
15	Outdoor	280
Westinghouse Electric and Manufacturing Company		
115	Oil-immersed Self-cooled	433

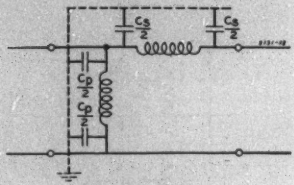


Figure 18. Capacitance distribution for induction regulators

Thus the effective capacitance at the source end is equal to $(C_P+C_S)/2$ while the effective capacitance at the load end is $C_S/2$.

Effective values determined from test readings obtained from regulators on the Philadelphia Electric Company system are shown in Table X.

Current-Limiting Reactors

An average value for the effective capacitance at each line terminal is approximately 100 micromicrofarads in the usual cell structure regardless of rating.

Generator Windings

General Electric Company. The following equation for the total capacitance per phase for generator windings has been taken from Park and Skeats' paper:[3]

$$C = K_e \frac{\text{mva}}{\sqrt{\text{kv}(1+0.08\,\text{kv})}} \text{ microfarads}$$

where the constant K_e has the following values:

Solid round rotors	0.0187
Salient-pole generators without amortisseurs	0.0347
Salient-pole generators with amortisseurs	0.0317

and

mva = rated capacity of generator megavolt-amperes

kv = rated line-to-line voltage of generator in kilovolts

One half of the value obtained from the equation should be considered concentrated at each end of the generator winding.

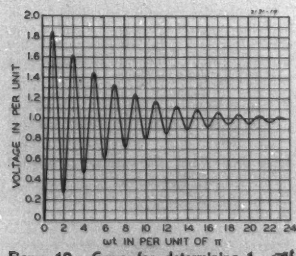


Figure 19. Curve for determining $1-\epsilon^{-\alpha t}\cos\omega t$ for decrement to 20 per cent in five cycles

$1-\epsilon^{-0.0321\alpha t}\cos\omega t$

π in microseconds for any frequency $= \dfrac{10^6}{2f}$

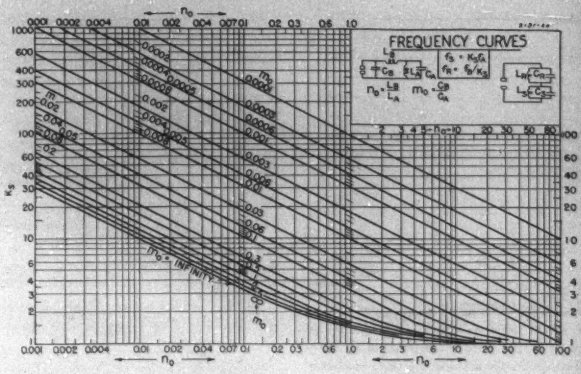


Figure 20. Frequency curves

Westinghouse Electric and Manufacturing Company. The effective capacitance per phase (one half the total capacitance per phase) is given in Figure 15 for salient pole generators, and in Figure 16 for turbine generators.

Oil Current Breakers and Bushings

The capacitance of an oil circuit breaker consists principally of the bushing capacitances. The values given in Table XI are for one bushing or for one side of an open breaker and should be multiplied by two where the circuit passes through the breaker.

The capacitance of General Electric Pyranol-filled bushings is approximately the same as that of similar oil-filled bushings.

General Electric type *H* breakers—15-kv (including bushings)

One tank to ground	125 micromicrofarads
Both tanks to ground	150 micromicrofarads

Insulators

SUSPENSION-TYPE

Standard duty (Westinghouse)	23 micromicrofarads
Higher strength (Westinghouse)	25–28 micromicrofarads

LOCKE INSULATORS

Rating and capacitance of Locke insulators are shown in Table XII.

BUS SUPPORTS AND WALL BUSHINGS

Indoor bus supports	12–25 micromicrofarads
Wall bushings	100–200 micromicrofarads

Lightning Arresters

General Electric Company. Approximately 20 micromicrofarads. However, this is subject to considerable variation depending upon design and voltage rating.

Determination of Capacitance by Flux Plots

In order to determine the capacitance of a bus or of a conductor by this method,[3] a cross section of the conductor in the cell should be drawn to scale. If there are any grounded parts running through the cell, the flux path will be from the conductor to these parts. However, if the conductor is surrounded by a concrete cell, the walls of the cell can be assumed as ground potential, and the capacitance calculated on this basis.

In the space between the conductor and the grounded parts or cell wall, draw equipotential surfaces and draw lines of flux

Figure 21. Magnitude curves

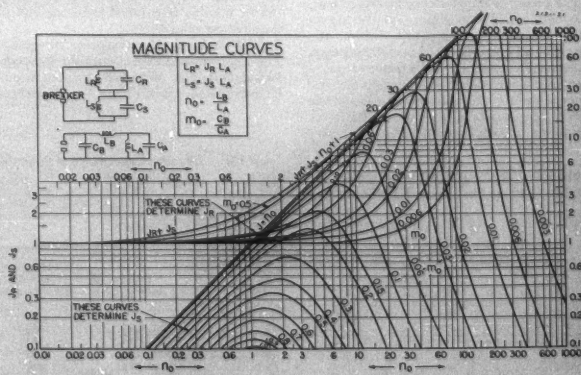


Table X. Effective Capacitance of Induction Regulators

Regulator Rating and Make	Effective Capacitance: Source End Micro-microfarads	Effective Capacitance: Load End Micro-microfarads
75-kva, 300/600-ampere, 2,500-volt, single-phase General Electric	6,250	2,250
72-kva, 300/600-ampere, 2,400-volt, single-phase Westinghouse	8,750	5,500
48-kva, 200/400-ampere, 2,400-volt, single-phase Westinghouse	4,750	2,500
34.5-kva, 150/300-ampere, 2,300-volt, single-phase General Electric	3,600	1,600
36-kva, 150-ampere, 2,400-volt, single-phase Westinghouse	3,300	1,500

from the conductor to ground. These should be so drawn that the lines of force and equipotential surfaces cross at right angles, and so that the cells formed are approximately squares. The lines of force should leave the conductor and enter the grounded surface at right angles.

The capacitance of the section can then be determined by counting the number of tubes of flux between the conductor and ground and the number of cells in series in each tube and by calculating the capacitance from the following formula:

$$C = 2.7\frac{w}{l}$$ micromicrofarads per foot of length of conductor at right angles to the paper where

w = the number of tubes of flux

l = the number of cells in series per tube

Fault Capacitance

The capacitance for a three-phase ungrounded fault consists of the capacitance to ground of the three conductors and of any equipment adjacent to the fault. Usually the capacitance of the cable or line will predominate and that of the apparatus will be negligible in comparison.

Any line or cable may be assumed, with little error, to be open at its far end. If such a line is short, it will behave substantially as if all its capacitance were lumped at the fault. If the line is long, on the other hand, it will behave for a considerable time like a resistance rather than a capacitance. Nevertheless, in the interest of simplicity, it is very desirable to represent the line as a capacitance; but if the entire capacitance of a long line is used, the resulting calculation gives an initial rate of rise which is much too low, and accuracy in this component is more important in the early part than later on. Consequently, an approximation has been adopted which consists in placing a limit on the length of line taken into consideration. This limit is set at a value such that the first reflection from the far end of the line, as limited, returns to the fault point after one-fourth cycle of the oscillation resulting from the corresponding value of capacitance in combination with the inductance of the return circuit.

This limits the error in the first part of the transient to a maximum of about seven per cent of the total circuit voltage. In general, this maximum error will not occur at the time of an important peak in the recovery transient, and hence the effect on the recovery rate from this source will usually be quite small. This limit in miles of line is given by the equation:

$$M = \left(\frac{\pi}{4}\right)^2 \frac{L}{l}$$

where

M = limiting line length in miles

L = inductance of the return circuit in henrys

$l = 1/3$ zero phase sequence inductance in henrys per mile

If M as calculated is equal to or greater than the actual length of the line, the actual length of the line should be used in determining the fault capacitance. If M is less than the actual length of the line, this value should be used for the length of the line in determining the fault capacitance.

Table XI. Effective Capacitance of Oil Circuit Breakers

Breaker or Bushing Rating Kv	Amperes	General Electric Company*: Without Capacitance Tap Micro-microfarads	General Electric Company*: With Capacitance Tap Micro-microfarads	Westinghouse Electric and Manufacturing Company†: Micro-microfarads
15	600	196		
	1,200	196		
	2,000	315		
	3,000	380		
25	600	160		100–300
	1,200	160		
	2,000	270		150–425
	3,000	335		250–500
				300–700
34.5	600	150		
	1,200	150		
	2,000			
	3,000			
46	600	145		
	1,200	145		
69	600	126	230	150–275
	1,200	126	230	
92	600	163	280	
	1,200	163	280	
115	600	163	294	250–315
	1,200	163	294	
138	600	160	306	300–375
	1,200	160	306	
161	1,200	155	310	340–435
196	1,200	235	390	
230	1,200	240	400	425–525
287	1,200			400–500

* Values apply to present standard bushings but will serve as a reasonably accurate approximation for bushings which are no longer standard. The former standard 400- and 800-ampere bushings have the same capacitance as the 1,200-ampere bushings listed here.

† Capacitance increases with rated continuous current and rated interrupting capacity.

Table XII. Locke Insulators

Catalog No.	Rating Kv	Capacitance of 1 Unit Micro-microfarads
29,150	15	15
10,455	34.5	25
9,153	46	11
7,785	115 (3)*	56
9,473	7.5	61
23,070	15–23	60

* Three units of 7,785 are used for 115 kv. Above value is for one unit. Three units will have approximately one-half the capacitance of one unit

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Electric Facilities and Operating Plan for the First Chicago Subway

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NONMEMBER AIEE

Synopsis: The $64,000,000 subway project now being completed will provide long-needed rapid-transit terminal facilities in the Chicago downtown district. The State Street subway will be completely equipped and in operation early in 1943 and will constitute a major contribution to the problem of handling additional traffic resulting from a decrease in the use of passenger automobiles.

This first subway route is five miles long and with fixed equipment will cost almost $34,000,000. The subways were built with track sections in tunnel—at low level. Platforms 500 feet long are provided at stations, except in the congested area where there is a continuous island platform 3,300 feet in length with access provided by mezzanine stations in each block.

All fixed equipment is being installed by the city. Despite the delay in securing equipment because of present scarcity of critical materials, the entire project will be built and equipped in a period of four years. This high-speed construction program required expeditious planning of locations for all electric facilities.

Power will be 600 volts direct-current. The 144-pound contact rail will be energized by existing substations and energy delivered by conventional positive and negative feeders, with contact rails reinforced with parallel feeders.

Adequate sectionalization of the entire system is provided largely by automatic operation. Centralized supervisory control of the all-relay type includes most modern accessories, such as an illuminated diagram board and remote-control dispatching equipment.

Train movements will be controlled throughout by a modern signal and electropneumatic interlocking system with automatic stops. Signals are spaced and timed for operation of 40 trains per hour on each track. Signals and other electric facilities, including lighting, pumps, fans, and escalators will have a-c power supply.

Fluorescent lamps will be utilized at all subway stations. Lighting intensities on mezzanine floors and station platforms will vary from six to eight foot-candles. Escalators are provided at all stations. At the downtown and heavier outside stations two four-foot escalators are provided operating at a speed of 90 lineal feet per minute.

The State Street subway will be operated initially by 455 steel cars now owned by the Chicago Rapid Transit Company. However, new equipment will be modern streamlined articulated units. The ultimate capacity of the State Street subway as thus equipped will be 80,000 passengers per hour.

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The Initial Subway Project

THE $64,000,000 subway now being completed, is the first step in a comprehensive plan for modernization and extension of all local transit in Chicago. The second step, now well under way, will be the consolidation of three separate and competing transit companies into a single unified corporation. This will result in economies in operation and the elimination of unnecessary and costly duplication of service.

The unification ordinance, granting an indeterminate franchise to the new unified company, has been passed, and virtually all of the preliminary steps taken, so that there now remains only the formal approval by the present security holders of the reorganization plan, the approval of the issuance of new securities by the Illinois Commerce Commission, and the final approval by the voters at a referendum to bring to its final culmination this objective which the city has sought for more than 25 years.

The third step will follow the granting of an indeterminate franchise to the new company and will consist of a thoroughgoing modernization of transit equipment, the substitution of trolley and motor busses for inefficient trolley-car service on about one third of the track mileage of the present surface-lines system, the extension of and improvement of service in intermediate and outlying areas of the city, not now adequately served with local transit, and the unification of all facilities through universal transfer between rapid transit and surface routes.

Function

An understanding of the function of the new Chicago subways requires a brief outline of the present local transit situation.

More than three quarters of the city's traffic is carried by the Chicago Surface Lines, operating a comprehensive network of street-car and, in more recent years, trolley-bus and motor-bus routes. During the last two decades, this surface transportation system has been supplemented by the operation of motor-bus routes, largely over the boulevards, by the Chicago Motor Coach Company, now carrying about seven per cent of the total traffic. The only form of urban rapid transit, other than that afforded by steam-railroad suburban roads, is that provided by the elevated railroad system operated by the Chicago Rapid Transit Company. However, unification of these companies will bring universal transfer and thus making rapid-transit facilities indirectly available to all.

For years engineers have realized the inadequacy of the downtown terminal facilities of this system. Thirteen elevated tracks, four on the north side, six on the west side, and three on the south side, deliver their loads to a two-track loop in the center of Chicago (except for a limited number of trains handled in stub terminals).

One of the principal objectives of the State Street subway is to provide terminal facilities for the rapid-transit lines to relieve the elevated loop. The loop, about two miles around, consists of two tracks both operating in the same direction. The cars using the inner loop must cross the outer-loop tracks at grade on both entering and leaving.

In spite of interference between all trains at two points, the outer loop now carries at the peak of service 208 cars in 35 trains during the maximum 30-minute period—see Figure 1. The inner loop now carries 167 cars in 36 trains. Commonly accepted practice to move trains expeditiously is a maximum of 40 trains per hour, and the heavily traveled New York subways operate at a lesser frequency than this. As a result of this congestion, speeds on the Chicago elevated loop lag down to six or seven miles per hour, and overcrowding of trains results—even under present traffic conditions.

The importance of additional terminal tracks for the Chicago rapid-transit system became vastly more important with the order rationing passenger automobile tires which became effective about the first of the year 1942. It has become evident that public transportation agencies will be required to carry, not only the additional traffic resulting from the accelerated pace of commerce and industry due to war activities, but also an ever increasing group of passengers who now use auto-

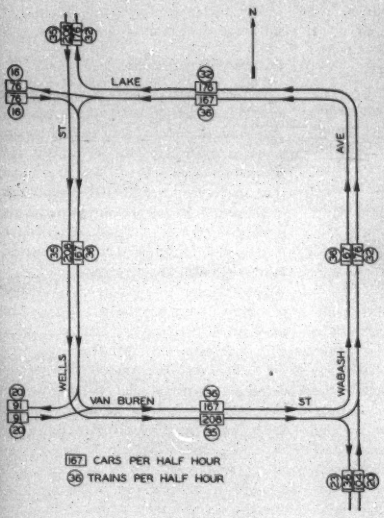
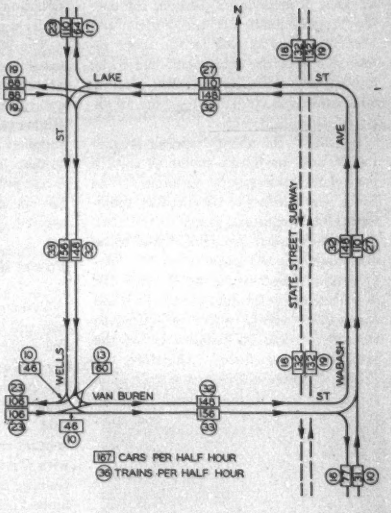


Figure 1 (left). Chicago rapid-transit car flow on the Union Loop during maximum half hour, 8:15–8:45 a.m., December 1941

Figure 2 (right). Car flow on Union Loop and State Street subway during maximum half hour, 8:15–8:45 a.m., expected in December 1942



mobiles exclusively for their transportation.

Because most automobile traffic to and from Chicago's downtown district is long haul traffic, it is estimated that most of the present automobile passenger load will be transferred to rapid-transit trains. Our estimates indicate that unless relief is afforded by the operation of the State Street subway during the year 1943, it will be virtually impossible to operate enough cars over the existing union loop terminal to provide transportation with any reasonable loading standard. Figure 2 shows the estimated redistribution of present traffic after the start of operation of the State Street subway.

Description of Subways

The initial project consists of two terminal subways which will be operated with and become an integral part of the rapid-transit system. Route 1, the State Street subway, connects with the four-track north-side elevated route near Armitage Avenue, 2½ miles to the north, and extends along Clybourn Avenue, Division Street, and State Street to a connection with the three-track south-side elevated route near 16th Street, 1½ miles to the south. This subway has a total length of 4.9 miles and is estimated to cost $33,750,000 including fixed equipment.

Route 2, the Dearborn Street subway, is the first unit of an underground terminal system for west-side rapid-transit routes. The initial section extends from a downtown terminal loop to a connection with the Logan Square elevated route, 3½ miles to the northwest of the downtown district. The total length of route is 3.9 miles, and the total cost, including fixed equipment, will be approximately $30,400,000. Except for short sections near the terminals, the entire project was built with track sections in tunnel at low level. Reinforced concrete tunnel sections were utilized throughout.

At each station platforms 500 feet in length are provided. At the three side-platform stations these structures consist of multiple arches—largely of reinforced concrete construction. Stations with continuous island platforms 22 feet in width were built in the loop district proper. This construction consists of a multiple three-arch section—two large bores on each side accommodating the trains and a portion of the platforms, with a smaller arch sprung from longitudinal steel girders supported by heavy steel columns. In general, stations are of the mezzanine type, constructed by cut-and-cover methods and located as close as possible to the street surface. Figure 3 shows an artist's perspective of the subway structure at a station.

All architectural features were designed with a view to providing attractive, light, and well-ventilated stations. A type of finish is planned which, in addition to being attractive, will stand wear and tear as well as the rigorous atmospheric conditions of downtown Chicago.

As finally developed the plans for the mezzanine stations provide for reddish-colored cement floors, scored in a tile pattern, light-colored structural glass walls, painted concrete ceilings, with dark (radio-black) marble column encasement, and metal doors and trim. Stairways have abrasive tile treads and glazed tile walls. The platforms are also to have colored cement floors, scored, with various colored paints on metal columns and all exposed metal—also on the arched ceilings.

Construction

Electrical Problems

Since the subways were tunneled through the soft clay underlying most of the city, air pressure was used during mining operations, and one of the first electrical problems confronting the subway department was the regulation of the contractors' electric facilities, including the service transformers, motor-driven air compressors, temporary electric lighting and hoists. The specifications were written to provide safety to the men working under air pressure in the tunnels. To insure reliability the power company was required to provide two entirely separate feeders from separate substations to each plant, each supplying a separate bank of transformers. Transfer switches were required as well as high-class equipment and wire throughout. Tunnel lighting and air compressors were especially safeguarded against failure.

The design of the permanent electrical work in the structure had to be made far in

advance of installation, because the conduit requirements for the feeders and branch wiring, as well as the space requirements of the equipment, had to be known before the concrete was poured. This subway is virtually free from all exposed wiring and cable.

Splicing chambers, circuit-breaker rooms, and machinery rooms all form a part of the underground structure. The space requirements of these rooms, therefore, is an important factor in the cost, and the electrical department had to be able to justify all space asked for. Arrangements had to be made with the power company for duct connections and transformer vaults, where necessary, so that these could be installed before the excavation was closed. Therefore, the electrical studies were intensive, even while the mining operations were just beginning.

Equipment Installed by City

Under the provisions of the unification ordinance passed in 1940, the new transit company is obligated to install all equipment in city-built subways. However, by the spring of 1941 it had become apparent that the seemingly interminable delays incident to completing all preliminary legal and financial negotiations might result in the first subway being completed before the reorganization was effected.

Therefore, the City Council, in May 1941, by ordinance directed the Commissioner of Subways and Superhighways to purchase and install the fixed subway equipment and to make arrangements with the trustees of the Chicago Rapid Transit Company for subway operation. Subsequently, the department proceeded vigorously with this work with the understanding that the city will be subsequently reimbursed for all equipment expenditures by the new transit company. In this task our engineers have had the full co-operation of the engineering staff of the Chicago Rapid Transit Company.

Progress

Basic subway construction on route 1 is complete. The elevated-to-subway connections at termini are now under construction. Station finish, much of which was redesigned to reduce the quantity of critical war materials, is now 50 per cent complete.

Anticipating some difficulty in securing the large quantities of steel, copper, and rubber required for fixed subway equipment, orders were placed and contracts let for furnishing most of the necessary equipment late in the year 1941. The last such contract, for signals and interlocking, was placed during April 1942; subsequently, contracts have been awarded for the installation of all traction power distribution equipment—work which is now under way.

The War Production Board has recognized the importance of completing the State Street subway by assigning a project rating of A-10 in February 1942. Higher ratings have been assigned various suppliers and manufacturers as required, so that the completion of the entire State Street project, including equipment, ready for operation early in 1943, now seems assured.

Power System

Trains operating in the State Street subway will be routed through the subway in the central area from the present outlying elevated terminals. The power for the subway trains will therefore be the same as that used on the elevated system, that is, 600-volt direct-current on the contact rails with paralleling feeders and with a return to the substations through running rails, negative feeders, and, to a limited extent, through steel elevated structures.

Substations and Feeders

Because the State Street subway is generally parallel to the present north and south elevated route, and because the downtown terminal traffic will be transferred from the elevated system to the subway, the subway power requirements will not be entirely in addition to the present system power requirements. Therefore, it is practicable to use existing substations now supplying the transit system. In most cases, these substations are actually adjacent to the subway structure, although one, the Sedgwick Street substation, is several blocks distant. New feeders will connect substations to the subway.

The substations are owned and operated by the Commonwealth Edison Company and under present plans this company will supply traction power to the subway. In general, the only new substation equipment required for the subway will be feeder circuit breakers and their automatic and control features.

The underground positive and negative feeders from the substations to the subway cable shafts will be paper-insulated, lead-covered cable. They will be spliced to water-resisting compound insulated feeders leading from cable shafts to circuit-breaker rooms in the subway structures. All power feeders in the subway will be insulated with water-resisting compound and finished with heavy asbestos braid. The subway circuit-breaker rooms at feed points will contain circuit breakers which will act as remote-controlled disconnect switches between these substation feeders and contact-rail feeders.

Contact-Rail System

A new contact-rail section has been adopted, similar in design but considerably heavier than that now used on the elevated system. This rail weighs 144 pounds per yard and will have a conductivity equivalent to 2,250,000 circular mils of copper. The rail will have a hardness somewhat greater than has been used for high-conductivity rails on other subways, to obtain longer life.

Since the contact rails are not generally of sufficient conductivity for the subway loads, it is necessary to reinforce them with paralleling feeders. These reinforcing feeders will be insulated with water-resisting compound and tapped to the contact rails at intervals of approximately 1,000 feet through disconnecting tap switches. The negative reinforcing feeders, in parallel with the running rails, will also be insulated with water-resisting compound and will be tapped to the running rails at intervals of approximately 400 feet. The positive and negative reinforcing feeders will be carried in a duct bench containing 12 asbestos-cement conduits along one side of each track in the train sections. The duct bench also serves as an emergency walkway—see Figure 4. Splicing chambers are located at 250- to 400-foot intervals.

The taps to the contact rails and running rails will be cables similar to the reinforcing feeders and are carried in asbestos-cement conduits in the concrete track ballast to pothead terminals, from which flexible bare bonds will connect to the contact or running rails. The location and gauge of the contact rail will be the same as that of the contact rail on the elevated system, so that the same collecting shoes can be used. This type of contact shoe is of the suspended overrunning contact type. The contact rails will be mounted on porcelain insulators on the track ties in the usual manner. Expansion and contraction will be taken care of by gaps at intervals of approximately 1,000 feet on level tangent track in the subways and at shorter intervals on curves and grades.

Sectionalizing

The contact rails with their reinforcing feeders are sectionalized at the substation feed points, interlocking plants, the emergency track crossovers, and at the tie points which are approximately midway between feed points. Short-circuit and overload protection on any section between substations is obtained by automatic opening of substation circuit-

Figure 3. Artist's perspective of the subway structure at a downtown station

breakers and tie circuit breakers without affecting other sections. The other sectionalizing circuit breakers do not have automatic opening features but serve as remote-controlled disconnect switches with high interrupting capacities. The function of the automatic circuit breakers at tie points is to connect the contact rails and feeders of the two tracks together in order to utilize the conductivity of both for feeding distant loads.

The tie station circuit breakers, the substation circuit breakers and all sectionalizing and disconnect circuit breakers will be of the latched-in, air-break type and will be remotely controlled by the supervisory control system.

Return Circuit and Bonding

Since the block signal system of the subway tracks will be of the single-rail track circuit type, one rail of each track will be used exclusively for signals, leaving only one rail of each track available for the traction current to return to substations. Each running rail will have conductivity equivalent to approximately 1,000,000 circular mils of copper. This conductivity must be supplemented by the negative reinforcing feeders. Running rail joints will be welded, except at special track work where bonds will be required across joints. Bonds will be bare flexible copper cable with terminals suitable for welding to the head of the rail by the oxyacetylene welding process.

The contact-rail joints will not be welded, so they must be bonded. The contact-rail bonds will be short U-shaped cable bonds located underneath the rails with terminals welded to the flanges. There will be two 750,000-circular-mil copper bonds per joint.

Supervisory Control

Due to the physical extent of this project and the diversity of operations associated with power services for a subway, including ventilating and pumping systems, centralized control and supervision is essential. This is to be provided by supervisory control of the all-relay type.

The dispatching equipment of the supervisory-control system will be located in the power supervisor's office, two blocks from the State Street subway. Remote station supervisory-control equipment will be located at eight control centers.

A power supervisor's desk, an illuminated diagram board, and relay cabinets of the swinging panel type will comprise the principal elements of the dispatching equipment. Although these elements will incorporate dispatching equipment for all eight outlying centers, the equipment will function independently for each. Thus operations of any given center will not interfere with simultaneous functions of another center.

The functions to be performed include remote control and supervision of all feeder, sectionalizing, and tie-station d-c circuit breakers, as well as the operation of the two-speed station and tunnel ventilating fans. Additional functions will include supervision of the continuity of the normal and emergency a-c services, high water level and pump-motor overload, low supervisory-battery voltage, battery ground or ground on control wires to apparatus remote from the control center.

The supervisory-control system is an "all-relay" system using relays of the standard telephone type, having uniform mechanical construction, extreme simplicity, and established dependability. Operation of this system is based on codes of

Figure 4. Duct bench and walkway during construction

impulses suggestive of a simple telegraph system, but different from the telegraph in that the impulses are all of the same time duration. Several impulses in uniform sequence form a code, and the number of impulses in a code is varied to obtain various results. All codes are produced automatically, the dispatcher's action being limited to the simple twisting of a control key and the pushing of a button.

As an example of operation, assume that it is desired to close a circuit breaker. The dispatcher first operates the selection key on the escutcheon of the desired breaker. This sets the proper relays into operation to select the breaker. As soon as this selection is made, the fact is indicated by the lighting of the white selection lamp on the associated escutcheon, as well as the lighting of a similar selection lamp on the diagram board. The supervisory equipment now comes to rest, awaiting the will of the dispatcher. Then, to close the breaker, the dispatcher first places the twist-type control key in the closed position and then operates

the master control key. This results in the closing of the breaker. When the breaker closes, the auxiliary signal contact closes and energizes supervision relays which operate to change the indications of the red and green supervision lamps on the diagram board. The supervisory control equipment then returns to the normal rest position, ready for the next operation or change in indication.

The system is operated entirely from 48-volt storage batteries to insure against loss of control from loss of a-c power. A check-back feature is employed as a guard against the possibility of obtaining false indications or performing false operations. Multiconductor control cable will provide the necessary channels for operation of the supervisory-control equipment. Each of the eight remote supervisory centers will be controlled and supervised over a single pair of wires. In addition to the pair per station, there will be two standby pairs. One standby pair will be available to the five stations to the north of the dispatcher's office, and the second pair will be available to the three stations to the south.

Throw-over switches at all points will facilitate transfer to the emergency lines in case of trouble. An audible and a visual alarm will be given in the power supervisor's office in case any of the control lines are opened, grounded, or short-circuited. In addition, each line will be equipped with supervisory-control protectors which will function to clear any heavy surges which may appear on the line wires.

Emergency Alarm System

Adjacent to splicing chambers located at intervals of about 400 feet along each subway track, emergency alarm boxes will be located on the walls above the walkways. These alarm boxes will be similar to city fire-alarm boxes in that when the lever on one of them is pulled, an alarm is given at the power supervisor's office. The alarm will be audible and visible, and the number of the box on which the lever is pulled will be recorded on a tape together with the time and date. Also, the pulling of an alarm-box lever will immediately open all circuit breakers through which power is normally supplied to the contact-rail section where the alarm box is located. Thus, in case of an emergency, such as a train wreck or fire, the motorman of an affected train, or other employee, can quickly de-energize the contact rail and at the same time give the alarm at the power supervisor's office. A telephone will be located by the side of each alarm box to enable the person actuating the alarm box to give further information and ask for and receive instructions concerning the emergency.

The alarm circuit will be a single-wire loop connecting all boxes in series. Each alarm box, when its lever is pulled, will cause a spring-driven contactor to open and close this loop circuit automatically at intervals in a code corresponding to the box number. If levers on two to four different boxes are pulled at the same or nearly the same time, each will transmit its code in turn, and all signals will be received at the supervisor's office without interference. The loop circuit will have automatic line supervision which will cause a distinctive alarm signal to be transmitted and recorded, in case of a ground or open circuit on the loop. The source of current for the alarm circuit and recorder will be a 48-volt storage battery at the power supervisor's office.

The circuit breaker tripping circuits will be an individual series loop for each contact-rail section. The opening of one of these loops will effect the de-energizing of the contact-rail section by means of relays, causing the supervisory-control tripping relays to trip the breakers. The alarm-system tripping relays are so designed that the power supervisor can reclose the circuit breakers by supervisory control after a short interval. The source of current for the alarm system's tripping loops will be the storage batteries at the outlying supervisory-control centers.

Signal System

The signal system consists of wayside colored-lights, approach interlocking signals, home signals, and interlocking dwarf signals. All of these except the dwarf signals have automatic controls; the approach and home signals are also controlled manually to govern train movements to and through interlocking plants. Dwarf signals (sometimes called backup signals) are manually controlled.

Automatic Train Stops

Associated with each automatic block, approach, and home signal there will be a wayside electropneumatic train-stop mechanism which in the tripping position would engage trip arms on the train thereby applying brakes and enforcing obedience to the STOP indication of the signal. A stop-release contactor mounted on the signal when operated by the motorman will clear the stop arm and permit him to pass a red signal when it is necessary to close up to the train ahead, or when signal or car-equipment failure occurs—according to the "stop, then proceed" rule.

Timing Control

The tracks are divided into blocks with a signal and train stop at the entrance to each block. The minimum length of a block is equal to the emergency braking distance for the expected maximum speed of a train as it enters the block, plus an additional length as a factor of safety. Minimum-length blocks are used in station timing where a train is allowed to close in at restricted speed when the station section is occupied. An illuminated T sign informs the motorman of the train where to begin this restricted speed. Signals governing entry into a station have extended controls so that the train standing in the station is protected by three or four red signals or by a distance sufficient to protect it from a following train traveling at maximum speed. The approaching train, on entering a track section or block where the T sign is located, energizes a time-element relay which picks up at a predetermined time and cuts off the extended control of the next signal, allowing it to clear for the train now traveling at a restricted speed. If this train continues at restricted speed, the next signal will have its extended control cut off by a second timing relay and so on, to bring the following train up closer to the station. This station timing is necessary to provide for the 90-second headway for which the signal system is designed. With no train standing in a station, all closing-in signals will be green, and a train can then proceed at normal speed.

On descending grades the braking distance is greater, and therefore the blocks at high speed would be so long as to reduce the track capacity. Restricting the speed of trains on grades results in increased safety and increased capacity. To accomplish this, "grade timing" is used with one or more signals normally showing the stop indication. If the trains run at excessive speed, a caution signal will be displayed, together with an additional lunar white indication, which indicates that the next signal is at "stop", only because the allowable speed is being exceeded, and that it will clear if the train runs at the permissible speed as measured by a timing relay.

These timing relays will receive coded energy for the measurement of the time intervals controlled by contacts on the track relays. The code transmitter, consisting of a coil, a mechanically tuned oscillator, and contacts, will generate the desired code for a number of time relays as determined by the location and distribu-

tion of these timing relays. Timing relays are also used for the emergency release of approach and route locking at interlocking plants. The time intervals will vary from four seconds for station timing to a maximum of 120 seconds for emergency switch operation.

Interlocking

At interlocking plants, switches and signals are controlled by means of buttons on a control board, and electric relay interlocking, in lieu of the mechanical locking which formerly was standard with interlocking machines. The control board is mounted on a desk within easy reach of the operator and has engraved on its face a miniature diagram of the tracks and switches of the interlocking plant, backed with lights repeating the track sections, thus showing the presence of a train as it approaches and moves through the plant. The interlocking control circuits are designed so that to initiate a route the operator need only manipulate a knob or button on the control board at the beginning of a route and then a second button at the end of said route. This operation causes the various switches and signals of the route to be correctly positioned and indicates on the control board that these switches have responded. This operation further electrically locks other switches and signals so that no conflicting move can be set up. Circuits are also provided for approach and sectional-release route locking which is standard in interlocking practice. Each switch and crossover has a separate operating lever on the control board for independent manipulation. An indication is also provided for each switch or crossover to show when they are not free to move, either because of the electric locking, or because a conflicting position of the switch has been called for.

The entrance control button has a red and a green lamp within it. The red lamp will flash when a route is initiated, will become a steady red light when the route has been completed, and will change to a steady green light when the signal has cleared.

Relays and Track Circuits

All relays are of the plug-in type with terminal prongs at the back. These prongs fit into sockets set into bases that are permanently mounted on racks. The control wires are soldered to these sockets. A maintainer desiring to replace a relay pulls one out of a socket and plugs in a duplicate without disturbing the wiring.

All interlocking and signal-control relays operate on ten volts direct current. Track relays are of the a-c vane type and operate over single-rail track circuits, where one rail is given over to signal track circuits, and the other rail is used both for power return and for track circuits. A track relay is connected across the signal and negative rails at the entrance to a block, while the approximately four-volt secondary winding of an air-cooled track transformer is connected across these rails at the far end of the block of track section. The relay and transformers are protected from unbalanced propulsion current by means of a resistance unit inserted in the leads to the signal rail and also by 600-volt fuses. The resistance unit in the transformer lead further limits the flow of current with a train in its track section. The track transformer has another secondary winding which furnishes ten-volt energy for lighting all signal lamps.

Signal Power Supply

The signal power-supply equipment is located in eight signal rooms in the State Street subway and at the north and south portal interlocking plants. Two liquid-cooled transformers at each location, one furnishing the normal supply and the other acting as a reserve source of power, receive energy at 60 cycles 208 volts in the subway and 240 volts at the two portals. The secondary circuits are interconnected by means of an automatic transfer switch and feed power to the a-c signal mains at 110 volts.

Two rectifiers of the copper-oxide type at each power-supply location are connected in parallel and feed power to the d-c signal mains at approximately 16 volts. These signal mains extend in each direction and in each tube from the power-supply source approximately half way to each adjacent supply location. The a-c signal mains feed the interlocking control-board lights, all signal lights, and track circuits. The d-c mains feed the relays at interlocking plants, all signal-line control relays, timing relays, and the electro-pneumatic valves.

Compressed Air

Air-compressor plants are located at the north-portal interlocking tower and at the 13th Street junction. Each compressor plant is equipped with two compressors connected to individual 600-volt d-c motors with automatic controls and fed from the propulsion current supply. The automatic controls are so arranged that either or both of the compressors may be cut in, depending on the drop in pressure. The compressed air is for operation of the automatic train stops and the track switches at interlocking plants.

Figure 5 (left). Front of typical a-c switchboard

Figure 6 (right). Typical pump room

The air distribution system consists of $1^1/_2$-inch air pipe extending the entire length of each subway tube and two-inch air mains on the elevated structure. Branch air lines feed compressed air at a normal pressure of approximately 65 pounds per square inch to the cylinders of the automatic stop and switch operating mechanisms.

Other Electrical Features

A-C Power Supply

The power for operating the a-c electric equipment will be supplied from frequent distribution centers along the subway by the Commonwealth Edison Com-

pany through 208/120-volt three-phase four-wire grounded neutral feeders. The total connected a-c load of the State Street subway and approaches (approximately ten track miles) is divided roughly as shown in Table I.

On this 4.9-mile two-track State Street route there are 21 a-c switchboard rooms in the subway, each supplied by duplicate service feeders from the Commonwealth Edison Company's transformer vaults. In the section outside of the central business district, the duplicate feeders are not merely parallel feeders; they come from normal and emergency sources, fed from different transformers. In the downtown area, the feeders come from transformer vault busses supplying the 208-volt three-phase network of the power company. These busses are interconnected with other vaults, and trouble in a vault supplying the subway would not interrupt services because of the network isolators. The reliability of the primary networks feeding transformers is well known.

Each a-c switchboard in the subway—see Figure 5—consists of a manually operated normal and an emergency service feeder main circuit breaker, on the load side of which is an electrically operated latched-in circuit-breaker type of automatic transfer switch to transfer the load from the normal to the emergency source in the event of failure of the former, and automatically transfer it back again on restoration of the normal source. In order to facilitate maintenance of the transfer switch there are by-pass and disconnect switches so arranged that the load can be by-passed around the transfer switch and the latter isolated, without interrupting the load. The remainder of the switchboard consists of the meter panel and branch feeder circuit breakers. The switchboards are all of dead-front steel construction with draw-out type of main service breakers. All circuit breakers are of the air-break type, main breakers having 50,000 amperes interrupting capacity, and the branch breakers in the switchboard 25,000 amperes interrupting capacity.

Pumps

The drainage pumps are located in pump rooms over sumps constructed below track level—see Figure 6. Each installation includes two pumps, one acting as a standby normally, and each consisting of a submerged centrifugal pump driven through a long shaft by a 208-volt three-phase squirrel-cage splash-proof motor automatically controlled by float switches. At locations where the subway crosses below the Chicago River the motors are located at the ground surface, and they drive the pumps below by 80-foot shafts. The motors—ranging from 5 to 50 horsepower—are equipped with line-voltage starters. In the State Street subway, there is a total of ten pump rooms.

Table I

	Kva
Lighting	270
Pumps	360
Fans	350
Escalators	370
Miscellaneous	280
Total	1,630

Ventilation

In general, it is proposed to depend upon the piston action of the moving trains for the normal ventilation of the tunnels, excepting in those portions of the tunnels which are at so great a depth as to make the cost of vent shafts to the surface prohibitive. These deeper sections of tunnel under the river will be ventilated by fans which can be operated continuously.

It is also proposed to depend upon the piston action of the moving trains for the normal ventilation of the stations, excepting the loop stations where the piston action will be somewhat ineffective.

Emergency fans will be installed midway between each pair of stations outside of the central district. In addition, small fans for the ventilation of toilet rooms and other service rooms will be provided in all of the stations. Vent shafts from train sections to the surface have been built on about 450-foot centers. The vent shafts near the stations have been located to serve a double purpose, namely, ventilation and blast relief for the station platforms. Without blast-relieving shafts at the tunnel entrances and exits of the stations, the high air velocities produced on the station platforms by the piston action of the trains would be intolerable. All of the openings in the tunnel walls to vent shafts will be equipped with power-operated louvers. These louvers will be interlocked with the emergency fans, so that when these fans are in operation, the louvers will be closed.

Two-speed reversible station fans will provide normal ventilation at the loop stations.

The horsepower of the fan motors ranges from 7½ to 60. All of the fans except one will be of the propeller type, six to ten feet in diameter, and belt driven. The motors will be two-speed three-phase squirrel-cage motors with splashproof frames. One fan will be of the centrifugal exhaust type driven by a 60-horsepower motor and will be used to ventilate a deep tunnel section that does not have ventilating shafts. There will be a total of 26 fan rooms in the State Street subway including 13 in the downtown stations. The fans will be controlled by the supervisory control system of the railway.

Lighting

The normal illumination of the subway will be by fluorescent lamps in the stations and over station platforms, and by incandescent lamps in the train tubes. Forty-eight-inch, 40-watt white fluorescent tubes will be used in the stations. The tubes will be mounted in single-tube fixtures with single-tube power-factor correcting auxiliaries mounted in the base. Each tube will be entirely enclosed by a frosted glass globe covering the lower half of the tube, and a reflector and the fixture base covering the upper half. The lighting fixtures and lamps are planned to produce lighting intensities varying from six to more than eight foot-candles on mezzanine floors and station platforms.

Sixty-watt incandescent bare lamps will illuminate the tunnels between station platforms. They will be provided with opaque shields on one side to protect the eyes of the motormen. The lamps will be spaced at approximately 30-foot intervals on each of two lines of lamps per tunnel. Every fourth light in the tunnels will be on a 600-volt d-c circuit, with 56-watt railway-type lamps connected five in series in a group. Emergency 600-volt lights in the stations will be incandescent lamps.

The a-c lights will be remote-controlled from the cashiers' booths in the stations,

Figure 7. Streamlined and articulated subway-elevated cars of the type proposed for Chicago

single-phase latched-in contactors closing the lighting circuits. In general, there will be two degrees of a-c illumination in the tubes and the stations, with space sectionalization. The 600-volt emergency lighting circuits will always be energized from one of two sources, with an automatic transfer switch being provided at each station for both tubes and station. A special 600-volt lighting cable running the full length of the tubes will be one of these sources, and the nearest traction positive feeder will be the other source.

All lighting loads will have duplicate feeders, one of which will be exclusively for the lighting load, and the other may serve other loads or act as a standby emergency feeder for one lighting load, while serving as a normal feeder for a motor load. Manual transfer switches will be used for some lighting loads when near a switchboard, but the tunnel-lighting feeders will have automatic transfer switches. This duplication of lighting feeders will be in addition to the triple reliability of three-phase, four-wire lighting circuits with single-pole subbranch breakers serving the same area. Thus, the importance of reliable illumination in a metropolitan subway is recognized.

Provision will be made for more intense illumination at the portals during daylight hours, to permit adjustment of the motorman's eyes to the comparatively dark tunnels, by flood lights located near subway portals. Control of these additional lights will be from outdoor photoelectric cells.

Escalators

For the reason that the grade of the subway platforms is generally 40 feet or more below the sidewalks, the escalator installation in the State Street subway is exceptionally liberal. There will be two escalators connecting the mezzanine level with the platform level at almost all stations. Escalators are attractively finished and will operate at a speed of 90 lineal feet per minute. The downtown station escalators are four feet in width, while those in lighter outlying stations will be three feet. All the usual safety devices will be provided. The escalators will be reversible and will be controlled by push buttons located near the top and bottom of each escalator. The horsepower required to operate the various escalators will vary from 16 to 25 each when fully loaded. This equipment was purchased late in the year 1940 at the total cost of $1,174,000 for both subway routes.

Transportation Features

Train Equipment

It appears that the subway will be ready for operation prior to the time new rolling stock is available. The war is likely to cause an extensive delay in securing modern equipment for the proposed subway service. Therefore, operation will be initiated with trains of existing steel cars of the Chicago Rapid Transit Company.

There is a total of 455 of these units available—389 of which are equipped with two 170-horsepower motors each—and 66 trailers. The seating capacity is 52 passengers per car, and the total capacity 100. These rapid-transit cars were originally designed for use in a subway and are well adapted for the purpose. Trains will be composed chiefly of motor cars, insuring high free-running speeds and rapid acceleration.

The problem of new rolling stock was thoroughly studied by a committee of engineers, organized at the suggestion of the city, composed of representatives of the Illinois Commerce Commission, Chicago Department of Subways and Superhighways, the Chicago Rapid Transit Company, and the Chicago Surface Lines. The committee, after investigating the needs of the subway and the type of car best-suited to meet requirements of modern rapid-transit operation, drafted specifications for a modern lightweight high-speed rapid-transit unit.

A streamlined articulated unit, consisting of three compartment bodies on four trucks, and weighing approximately 82,000 pounds complete without load, was proposed. The general type of car is illustrated in Figure 7. The seating capacity is 106 passengers, and the total capacity 200. Propulsion would be with eight motors totaling 440 horsepower, and the free running speed 45 miles per hour on level tangent track. Such a car would start and stop at the rate of three miles per hour per second under average operating conditions.

In planning the new unit, the committee sought to utilize as many as possible of the favorable characteristics and equipment of the PCC street car. The latter vehicle, which obtains its alphabetical name from the Presidents' Conference Committee sponsoring its development, has been successfully used during the past six years for surface city transit. It embodies many "passenger-comfort" features, such as wide clear-view windows, plentiful illumination, adequate ventilation, uniform distribution of heat, smooth rapid starts and stops, noiseless operation, and the easy riding qualities resulting from rubber springs and resilient wheel construction. The operation of these new units over the welded running rails of the subway tracks promises an innovation in smooth-riding quiet subway-train operation.

The initiation of service on the State Street subway with the 455 steel cars now being specially equipped for subway use will provide three-minute service in each direction. When additional rolling stock is obtained, the number of trains will be increased with the demands of traffic up to a maximum of 40 trains per hour in each direction, the limit of the track capacity.

Operation

The maximum capacity of two-track rapid-transit subways is calculated by assuming the operation of 40 trains of five articulated units per track per hour. Units with maximum dimensions of 9 feet 6 inches in width and 90 feet in length, and weighing about 41 tons, are contemplated. With an average loading of 200 passengers per unit such an operation would develop a capacity of 40,000 passengers per hour per track. Thus the total capacity of the State Street subway would be 80,000 passengers, or 40,000 during the maximum half hour. This total capacity may be compared with the present total combined load for rapid transit, street cars, and motor busses of less than 90,000 in the maximum 30-minute period. Considering the fact that convenience requires the retention of some local bus and trolley-car routes at street grade, it is apparent that this terminal subway layout will provide adequately not only for present but for future traffic for years to come.

The 3,300-foot long platform planned for the State Street subway in the loop district will provide space for three double stops—each about 1,100 feet in length. Separate berths will be provided at each station stop for trains operating in different directions, thus providing the broadest possible distribution of incoming and outgoing passengers along the platform and through escalators, turnstiles, and stairways.

A New Multiple High-Speed Air Circuit Breaker for Mercury-Arc-Rectifier Anode Circuits and Its Relation to the Arc-Back Problem

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Synopsis: Mercury-arc power rectifiers have been used increasingly to supply power to d-c utilization systems in the United States since the early twenties. War requirements, because they have multiplied the demand for aluminum, magnesium, chlorine, zinc, and copper, all of which utilize d-c current in their reduction, have tremendously increased d-c power consumption. It is estimated that 12½ per cent of the kilowatt-hours generated in 1941 were consumed in such electrochemical processes. Since the mercury-arc rectifier is now the almost universally accepted form of conversion apparatus for this purpose, the attention of many more engineers has recently been focused on it.

Many advantages of the modern rectifier have led to its wide acceptance, but it is not within the scope of this paper to deal with these. One persistent factor in connection with the application of rectifiers which has claimed much attention is the phenomenon of arc-back. Various methods of attack have been employed successfully. High-speed anode switching appears to be the most satisfactory way to handle this problem. Such a solution is widely used in the aluminum industry.[1]

Part I of this paper includes an analysis of the arc-back problem and various means of protection from its effects. Reasons why high-speed anode switching *is* an improved type of arc-back protection are set forth.

Part II of this paper describes this multipole high-speed air circuit breaker. The requirements which the breaker must meet are discussed, and the electrical and mechanical features described. Performance of the breaker was checked in field tests. Oscillographic data are presented and prove that the performance is acceptable.

Part I. Analysis of Arc-Back Problem

Definition of Arc-Back

ARC-back may be defined as a failure of the insulating properties in an arc rectifier during the inverse half wave which results in the rapid reversal of current through the rectifier element. When such an event occurs, there are usually manifestations of this failure, such as high short-circuit a-c current and reversal of d-c current normally flowing from the rectifier.

Various theories have been developed to explain the reasons for this occasional failure of rectifying property or arc-back.[2-4] One commonly accepted explanation is the "particle theory" developed by Doctor Kingdon.[3-5]

In this theory an assumption is made that a minute particle of insulating material, perhaps as small as 10^{-4} centimeter in diameter, becomes accidentally attached to the surface of the anode. Under certain conditions this particle may become charged by positive ions from the surrounding ionized plasma, and a positive voltage built up. Since the distance between the particle and anode is infinitesimal, a high enough gradient may be established between particle and anode to draw electrons from the anode surface (one to ten million volts per centimeter). When the anode emits electrons, it becomes a cathode, and the rectifier is in arc-back. The chances of such particles or patches becoming charged sufficiently to create arc-back is a statistical study.

Engineering Approach to the Arc-Back Problem

Ever since the first commercial mercury-arc power rectifiers were installed, engineers have struggled with the arc-back problem. Constant research and developmental work have been and will continue to be conducted to minimize the occurrence. It has even been the subject discussed at several informal conferences under the sponsorship of the AIEE electronics committee at winter conventions.

Rating and Arc-Back Frequency

Much progress has been made. During the past 15 years, reliable rectifier ratings have been increased from 750 kw per vacuum system at the outset[4] until today there are many units in very successful operation supplying as high as 3,750 kw per vacuum system.

For d-c output voltages below 300 the arc-back problem has not been difficult. Absence of arc-backs has permitted the engineer to base the ratings on thermal limits of the rectifier element and associated transformer equipment.

However, at higher voltages, increases in rating have required progress in the art of reducing arc-backs. Usually, the rating is based on the level of load which the rectifier will carry with acceptable arc-back frequency rather than on the thermal limits of the apparatus.

Anode Shielding

One of the most powerful means available to engineers of reducing arc-back tendency is to increase the deionizing shielding which is placed near the anodes. The shielding may be increased by placing more deionizing surface in the arc stream below the anode, by reducing the area of the holes in the grid through which the arc passes, by changing spacing and configuration, by increasing arc length, or by multiplying the number of grids. It must be realized though that most of these measures also result in increasing the arc losses and lowering the efficiency.

In the modern rectifier a satisfactory compromise has been reached. Sufficient shielding has been provided to insure acceptable performance as regards arc-back frequency. On the other hand, it has not been increased to the point where it has endangered the attractive higher efficiency that the rectifier usually possesses, as compared to other types of conversion apparatus. Sufficient shielding to reduce arc-back near the vanishing point would likely sacrifice that margin of efficiency.

Reactance

Another factor, which bears on arc-back tendency, is the value of reactance in the transformer supplying the rectifier, and in the a-c system supplying the a-c power. Engineers have learned that a given rectifier may arc back frequently when connected to a transformer and a-c system having certain reactance characteristics, whereas, the same rectifier may be completely free from arc-back for other circuits and reactance characteristics, even though the d-c output voltages and loads are identical. Advantage is usually taken of this factor in the struggle to minimize arc back.

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PROTECTIVE EQUIPMENT

Designing engineers, after having arrived at an economic balance between efficiency and shielding, have produced rectifiers which are relatively low in arc-back frequency. However, they know that they are unable to predict zero arc-backs. Therefore, they must depend upon protective equipment associated with the rectifier apparatus to eliminate the effect of arc-back, both on the electric equipment and on the continuity of service required.

Paths and Magnitudes of the Arc-Back Currents

In order to select protective equipment it is necessary to study the direction of current flow, its path through the various electric circuits, and the probable magnitudes involved. Figure 1 shows typical power circuits for two six-anode rectifiers operating in parallel on the same d-c bus, supplying a counter electromotive force load. Arrows indicate the direction of direct current in the various parts of the circuit when an arc-back occurs in one of the rectifying elements. Figure 2 indicates the behavior of current flowing in the important parts of the circuit shown in Figure 1 as they would be seen in an oscillograph. Steady-state values are typical of what would occur in many conventional rectifier installations if protective equipment were not provided. Current values shown are typical, being values measured oscillographically during representative tests on rectifiers rated 5,000 amperes 600 volts direct-current.

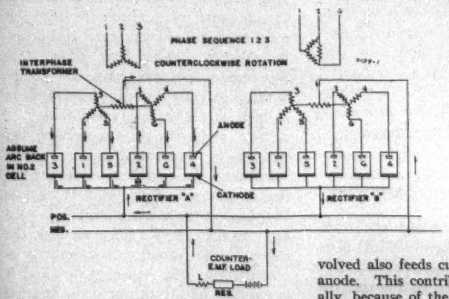

Figure 1. Direction of current in various parts of circuit when rectifier *A* arcs back

Accurate mathematical prediction of the current magnitude which would flow in a given circuit would be extremely difficult. The most important reasons for this are that reactance values in any transformer involved in an arc-back do not remain constant because of d-c saturation of the iron; and voltage drops in the arcs are not well known under the high current conditions obtaining. Usually such attempts give results in magnitude somewhat higher than test measurements. Therefore, studies of this sort are usually based on actual oscillographic tests. Certain general rules however, may be used to estimate the behavior of arc-back currents.

RULES FOR BEHAVIOR OF ARC-BACK CURRENTS

1. The reverse current flowing in the anode circuit of the rectifier element in arc-back consists of several components:

Contribution From Same Wye. The two other phases of the same transformer wye feed currents into the affected anode in turn as they commutate. Their magnitudes are limited by the commutating impedance of the rectifier circuit. This component is alternating or pulsating in character being displaced from the zero axis by action of the rectifier.

Contribution From Other Wye. The other wye of the rectifier transformer involved also feeds current into the affected anode. This contribution increases gradually, because of the initial high impedance of the interphase transformer. As the interphase transformer saturates due to undirectional current, its impedance decreases, and this contribution becomes greater. Its magnitude is determined by commutating impedance. This component is displaced from the zero axis by the action of the rectifying elements.

Contribution From Parallel Conversion Apparatus. Another component is fed from any parallel conversion apparatus such as other rectifiers connected in parallel to the same bus. This component is not pulsating being direct current in character. Its rate of rise is determined by the reactance due to air leakage fluxes throughout the circuit, both in the leakage spaces of the transformer windings conducting the reverse current and in the connections between the rectifiers. Final or steady-state magnitude of this component is limited only by the metal resistances of the station conductors in series, the resistance of one-half transformer secondary winding, the resistance of one-half the interphase winding, and the lumped or equivalent resistance of all contributing conversion apparatus in parallel.

Contribution From the D-C Load. If the nature of the d-c load is counter electromotive force, it too will feed current through the anode in arc-back. This component is d-c in character. Its rate of rise is determined by the air flux reactance of the circuits involved and its steady-state value by the total series metal resistance of the circuit.

2. All of these components add arithmetically to give the total reverse current at any instant carried by the anode in arc-back.

3. The effective voltage driving the short-circuit currents is reduced in proportion to the increase in arc drops caused by the higher currents passing through the arcs. Values for this increase in arc drop have been difficult to obtain, partly because of the transient and unpredictable nature of arc-backs and partly because of the instability of high-current arcs. Estimates of 50 to 100 volts are often used.

4. The effective driving voltage is reduced by a-c system regulation.

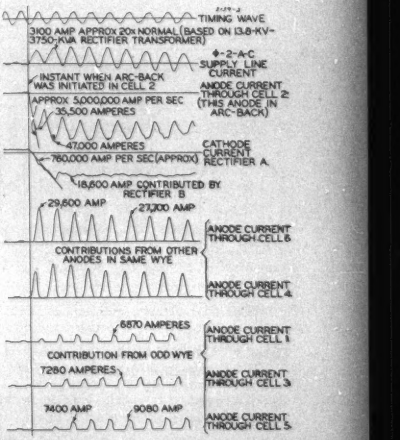
TIMING WAVE
3100 AMP APPROX 20% NORMAL (BASED ON 13.8-KV-3750-KVA RECTIFIER TRANSFORMER)
2-A-C SUPPLY LINE CURRENT
INSTANT WHEN ARC-BACK WAS INITIATED IN CELL 2
ANODE CURRENT THROUGH CELL 2 (THIS ANODE IN ARC-BACK)
APPROX 5,000,000 AMP PER SEC
35,500 AMPERES
47,000 AMPERES
CATHODE CURRENT RECTIFIER A
760,000 AMP PER SEC (APPROX)
18,500 AMP CONTRIBUTED BY RECTIFIER B
29,600 AMP
27,700 AMP
ANODE CURRENT THROUGH CELL 6
CONTRIBUTIONS FROM OTHER ANODES IN SAME WYE
ANODE CURRENT THROUGH CELL 4
6870 AMPERES
ANODE CURRENT THROUGH CELL 1
CONTRIBUTION FROM ODD WYE
7280 AMPERES
ANODE CURRENT THROUGH CELL 3
7400 AMP
9080 AMP
ANODE CURRENT THROUGH CELL 5

Figure 2. Behavior of current in various parts of circuit during arc-back

5. In practice it is found that the major contributions to the total reverse current are from the same wye and from parallel conversion equipment. The latter contribution is increased as the number and rating of paralleled conversion apparatus on the same d-c bus is raised. Such contribution theoretically reaches alarming proportions for many large electrochemical installations. It has been estimated that theoretical steady-state values of reverse current in an anode circuit might reach 600,000 amperes for certain large installations. (Anode reverse-current rates of rise for large installations have been measured and range as high as 10,000,000 amperes per second.)

6. Other anodes in the same rectifier unit or in other rectifiers on the same d-c bus are caused to arc back as a result of their high contributions to the first one in arc-back. It is doubtful if such theoretically possible high steady-state values as 600,000 amperes would be reached, and certainly they would not be maintained. Sympathetic arc-backs would always spread among the

associated rectifiers. End result would be that all rectifiers would become involved, and all contributions from parallel apparatus vanish.

7. Contributions from d-c loads usually are transitory. Rotating-type d-c loads come to a standstill quickly. Electrolytic loads are usually inductive, so that the current reversal is relatively slow, and rate of rise limited. Electrolytic-cell polarization voltages are usually only a fraction of the d-c applied voltage, and resistance drops are a large factor. Under short circuit such cells lose their polarity rapidly.

8. Current increases in the primary windings of the rectifier transformer corresponding (by transformer action) to the secondary currents. The values would be similar to those reached when all the secondary windings of such a transformer are short-circuited, except for the fact of the rectifying action and the higher-exciting currents due to d-c saturation in the iron. These factors increase the primary currents over the values that would obtain if all the transformer secondary windings were merely short-circuited.

Effect of Arc-Back Without Protection

The preceding analysis indicates that the high currents impose stresses on nearly all parts of the circuit. Various injurious results which could be expected if protective equipment were not provided may be listed as follows:

1. The a-c supply system may be overloaded. Increase in current supplied during arc-back often reaches 20 times the full-load current rating of the transformer.

2. The rectifier transformer would be damaged. Rectifier transformers are usually specially braced to withstand mechanical shocks due to arc-back. The duty caused by the high current in the windings connected to the anodes in arc-back would be particularly severe.

3. The rectifier element itself would be affected in several ways:

A. The higher currents would heat parts not previously degassed for such high currents and drive off gases which would impair the vacuum.

B. The high-current arcs would burn the metal walls of the vacuum chamber.

C. While the graphite anodes will withstand severe heating, continued presence of a cathode spot at the anode would remove material and roughen the surface.

4. Continuity of service would be interrupted, because other conversion apparatus on the same bus would be overloaded to the failure point.

Transients Which Signal Arc-Back

It is obvious that the sudden reverse and overcurrent conditions which appear in the circuits during arc-back offer ready means for signaling the event and actuating the protective equipment. A study of Figures 1 and 2 in the light of these requirements is worth-while. Current suddenly increases in the a-c supply lines and in all the anodes operating in normal forward-current fashion. However, these are symptoms of overload as well as arc-back. It is difficult by this means to distinguish arc-back from plain overload. If there is parallel conversion apparatus, a reliable indication of arc-back is the presence of reverse current in the cathode and negative connections. However, where a single rectifier feeds a purely resistance-type d-c load, no reversal occurs in these connections. The invariably present unmistakable evidence of arc-back is the presence of reverse current in the connection between the transformer secondary winding and the anode of the rectifier.

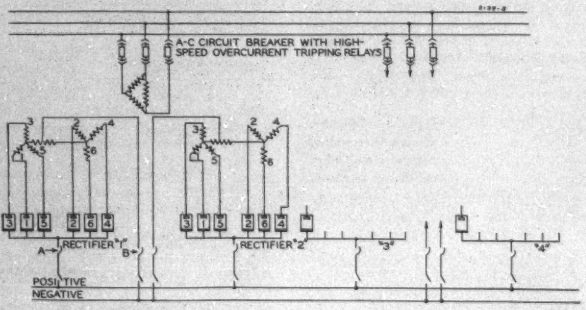

Figure 3. Cathode-switching arrangement of protective equipment

A—High-speed d-c circuit breaker with built-in reverse-current tripping action

B—Medium-speed d-c circuit breaker with time-delay overcurrent trip

Four General Methods of Arc-Back Protection

Broadly there are four methods of protecting from arc-back. Three of these have been used in conventional large power installations.

Reactance

First is the use of large reactance values to limit the arc-back currents. Often if the resulting flow of current is limited to relatively low values by reactance, the condition causing the arc-back at the anode disappears, and normal rectifier action is automatically re-established. This can be true only where no other counter-electromotive-force apparatus is connected to the same d-c system. This method is sometimes used for such rectifier installations as those furnishing high-voltage d-c power to dust precipitators, oil-cracking processes, and laboratory apparatus.

Arc Suppression

Second is the so-called "arc-suppression" method. Arc suppression—in the case of multianode rectifiers—consists of grid action to prevent anodes from firing; in the case of ignitron rectifiers—it consists of ignitron action and grid action to prevent anodes from firing. Arc suppression does not have the ability to interrupt current passing from anode to cathode once it has been established.

"Arc suppression" accomplishes its purpose by preventing anodes—which would normally contribute current to the one in arc-back—from firing in turn as they become successively positive in voltage. In the case of a single rectifier, the anode reverse current consists entirely of contributions from other anodes, and it is possible quickly to starve the affected anode and eliminate the arc-back. It should be added that, if other conversion apparatus is connected to the same d-c bus, the current which they contribute must also be interrupted. One method is to interrupt the reverse current in the cathode line by means of a high-speed d-c circuit breaker. Another method, assuming all other conversion apparatus consists of rectifiers, is to apply "arc suppression" simultaneously to all other rectifier elements connected to the same bus during arc back.

"Arc suppression," by means of grids, is accomplished by suddenly energizing the grid with negative potential. With a negatively charged grid between the anode and cathode spot, electrons are repelled, and the anode is often effectively blanketed so that it cannot fire. In the ignitron, the anode is prevented from firing by suddenly cutting off the electric excitation of the igniter point which creates a new cathode spot each cycle. Without the existence or creation of the cath-

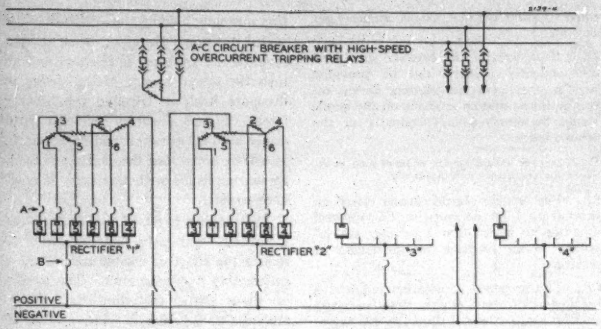

Figure 4. Anode-switching arrangement of protective equipment

A—High-speed multipole-anode circuit breakers with built-in reverse-current tripping action for each pole

B—Medium-speed d-c circuit breakers with time-delay overcurrent trips

ode spot in the mercury cathode pool, the anode should not fire.

Experience with "arc suppression," however, indicates that it is not always effective. Therefore, other backup protection in the form of protective switchgear is always provided to interrupt the overcurrents when "arc suppression" fails.

When it is successful, "arc suppression" is so rapid in action (one-half to two cycles) that it is not necessary for the a-c circuit breaker to open. The yardstick often used to measure the effectiveness of "arc suppression" is to record and compare the number of arc-backs accompanied by a-c breaker operations with those unaccompanied by a-c breaker operations. It is obvious that the relay or device which detects the presence of arc-back and actuates the "arc suppression" must be designed to operate in a small fraction of a cycle.

Experience indicates that "arc suppression" appears to be more successful in installations where reactance values are relatively high.

Cathode Switching

Third is the method most commonly employed until recently—that of disconnecting the rectifier and transformer from the system by means of circuit breakers. A typical arrangement is shown in Figure 3. In its best form it consists of an a-c circuit breaker with special high-speed induction-type a-c overcurrent relay protection, for each rectifier transformer, and a special high-speed reverse-current d-c air circuit breaker in the d-c side for each rectifier.

To illustrate the operation of the cathode-switching arrangement, assume an arc-back in cell 2 of rectifier 1—Figure 3. The following action takes place:

1. The d-c current reverses in the cathode line of rectifier 1. This action trips the reverse-current high-speed d-c breaker, which starts reducing the current in one-half to three-fourths cycle and interrupts the d-c circuit. Reverse current in the cathode line had been contributed by rectifiers 2, 3, and 4. This duty imposed overloads on these units and had started to operate the overcurrent tripping relays associated with the a-c circuit breaker supplying rectifiers 3 and 4 and all the negative d-c-line breakers. However, the high-speed action of the above reverse-current breaker usually should relieve the short circuit in time to prevent outages on 3 and 4, unless they too arc back sympathetically.

2. Even though the reverse-current contribution to cell 2 from the other parallel rectifiers is removed quickly by the high-speed cathode breaker, contributions from the other anodes in the same rectifier continue. Overcurrent relays associated with the a-c circuit breaker protecting the main transformer for rectifiers 1 and 2 therefore complete their operation, disconnecting the transformer and both rectifiers 1 and 2 from the a-c system.

3. Conventional a-c power-circuit breakers require a minimum of seven to ten cycles including relay time to interrupt an a-c short circuit. This means that the heavy duty imposed by the high arc-back current in both the rectifier element and the transformer winding continues throughout this time.

4. Two rectifiers connected to one transformer have been disconnected from service because of an arc-back in only one unit, as it was necessary to open the a-c power circuit breaker. Only rectifiers 3 and 4 remain in service.

Anode Switching

Fourth is the latest method of dealing with the problem. A high-speed air circuit breaker in the anode line interrupts the fault current resulting from the arc-back.

Such an arrangement is shown in Figure 4. In its best form it consists of a power circuit breaker with standard inverse time a-c overcurrent relay protection for each transformer primary winding, a special high-speed multipole circuit breaker in the anode circuits with reverse-current tripping action, and a standard medium-speed d-c air circuit breaker in the cathode line for each rectifier. To illustrate the operation of anode switching and compare it with operation of cathode switching, assume an arc-back in cell 2 of rectifier 1, Figure 4. The following action takes place:

1. The d-c current reverses in anode line 2. This action trips pole 2 of the high-speed multipole-anode air circuit breaker, which starts to reduce the overcurrent in one-half cycle or less and interrupts the arc-back current in less than one cycle. Current contribution from rectifiers 2, 3, and 4, as well as the other anodes in the same rectifier unit, are all cut off. The common circuit path where they all add up and flow has been opened.

2. Since the short-circuit condition in the

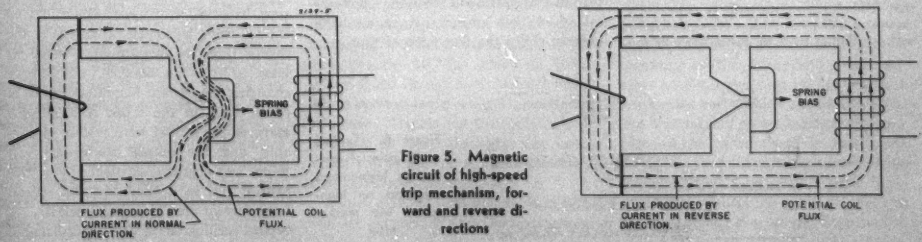
SPRING BIAS
FLUX PRODUCED BY CURRENT IN NORMAL DIRECTION
POTENTIAL COIL FLUX
SPRING BIAS
FLUX PRODUCED BY CURRENT IN REVERSE DIRECTION
POTENTIAL COIL FLUX

Figure 5. Magnetic circuit of high-speed trip mechanism, forward and reverse directions

transformer supplying rectifier 1 has disappeared in one cycle, its a-c overcurrent relay does not trip the main breaker. Therefore, the transformer remains energized, and rectifier 2 may remain in service.

3. High-speed action of pole 2 in interrupting the reverse current removed the overcurrent condition imposed on rectifiers 3 and 4 soon enough to prevent their outage.

4. Because the duration of short circuit does not last more than one cycle, only a small fraction of the same duty is imposed on both rectifier element and transformer winding of rectifier 1 as compared to the longer duty imposed with cathode switching when the overcurrent lasts 7–10 cycles.

5. The medium-speed cathode breaker can be interlocked with all poles of the anode breaker, so that the cathode breaker serving rectifier 1 would open, but without severe duty. Interlocking would be employed where it is inadvisable to allow a rectifier to remain in service without all anodes in operation.

Cathode switching for arc-back protection was adopted early in the history of rectifier application. It had wide acceptance, but "arc suppression" was later developed as recognition of some of the cathode-switching limitations, grew. Then when experience proved that "arc suppression" was not dependable under all conditions, and because wide use of rectifiers justified the effort, the high-speed anode switching was introduced. It now appears that the use of adequate high-speed anode breakers fulfills the requirements for arc-back protective equipment.

Part II. The High-Speed Air Circuit Breaker Developed

Basic Requirements

Before embarking upon the design of a new multipole high-speed breaker to satisfy the requirements of anode protection for mercury-arc rectifiers, a study was made to determine the prime requisites of this new breaker. These are as follows:

(*a*). The breaker should have a high opening speed. To clarify this it was determined that the breaker should start to reduce line current a half cycle or less (60-cycle basis) with maximum rates of current rise in the range of 2,000,000 to 6,000,000 amperes per second.

(*b*). Each pole of the breaker should be independently tripfree and be provided with a reverse-current tripping device, direct acting so that an arc-back on any anode would be removed independently of the other anodes.

1. A breaker should consist of six of such poles, closed simultaneously or individually.

(*c*). The breaker should remain closed on excessively high currents in the forward direction to insure that a rectifier not involved in an arc-back would remain in service.

(*d*). The proposed application required a breaker which could remain closed carrying load for long periods of time. It was therefore evident that existing switchgear standards should not be sacrificed in the interest of breaker opening speed.

There were other miscellaneous minor requirements attendant to the design of this new breaker, such as electrical closing, mounting, and so forth, which, while of interest to the designer, are not so pertinent to the discussion of this new high-speed breaker as the four preceding main requirements.

Design Problems

An analysis of the above requirements indicated that four major design problems were involved. These were as follows:

1. A high-speed current directional tripping mechanism.

2. A suitable breaker structure.

3. A current-interrupting device, compact in size, yet capable of coping with voltage in the order of 1,700 between phases.

4. A simple drive for operating a number of poles mechanically in parallel at a reasonably constant speed, regardless of the number of poles to be closed.

Trip Mechanism

The magnetic circuit of the tripping device selected is shown in Figure 5. The energy necessary for tripping the breaker on arc-back is stored in a compression spring restrained normally by the small armature. Flux provided by a potential coil normally holds the armature in the restrained position. A reversal of current caused by an arc-back quickly shifts the flux path of that portion normally holding the armature in the sealed position; therefore, upon current reversal the armature is released and allows the stored energy of the spring to dissipate itself in tripping the breaker latch. Figure 5 shows the flux path under normal operation and on arc-back. It will be noted that flux shifting is readily accomplished with this type of magnetic circuit.

The moving parts of the device were necessarily extremely light in order to reduce the effect of inertia and obtain a satisfactory operating time. The weight of these parts, excluding the spring, amounts to 2.4 ounces. The portion of the magnetic circuit in which the flux shifts, due to current reversal, was made of laminated silicon steel in order to facilitate the flux change. The magnetic circuit associated with the potential coil proper was made of solid iron and the iron surrounded with copper, so as to obtain a structure resistant to any sudden changes in applied voltage.

Since this device would be subjected to widely varying rates of current rise (in the order of 1,000,000 to 10,000,000 amperes per second), it was necessary to determine the effect of an extremely high rate of rise on its performance. It was conceivable that with an extremely high rate of rise of current in the tripping direction, the flux in armature would be reduced to zero and then built up in the opposite direction before the armature had moved sufficiently to be free of the influence of this flux. Such a condition would make the device inoperative and would prevent its functioning to trip the breaker. The level at which this would occur could be controlled by varying the inertia of the moving parts and by reducing the air gap of the poles bridged by the armature, the final air gap arrived at by test being in the order of $^{3}/_{32}$ inch.

A rather novel and interesting method was adopted to determine the effect of widely varying rates of current rise on the performance of the device. This consisted of testing the device in a low-voltage high-current a-c circuit. For a half cycle of current in the normal direction the tripping armature would not release, but on the following half cycle of current in the reverse direction this armature would release to trip the breaker. By simply changing the current magnitude, rates of current rise in the order of 23,000,000 amperes per second were readily obtainable, and the release mechanism was tested and operated satisfactorily at this rate of rise in a time of 0.002 second from current zero to point of release. A typical oscillogram of this performance is

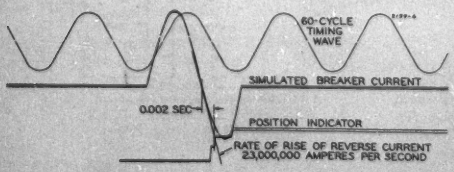
60-CYCLE TIMING WAVE
SIMULATED BREAKER CURRENT
0.002 SEC
POSITION INDICATOR
RATE OF RISE OF REVERSE CURRENT 23,000,000 AMPERES PER SECOND

Figure 6. Typical oscillogram of low-voltage high-current a-c tests on high-speed trip mechanism

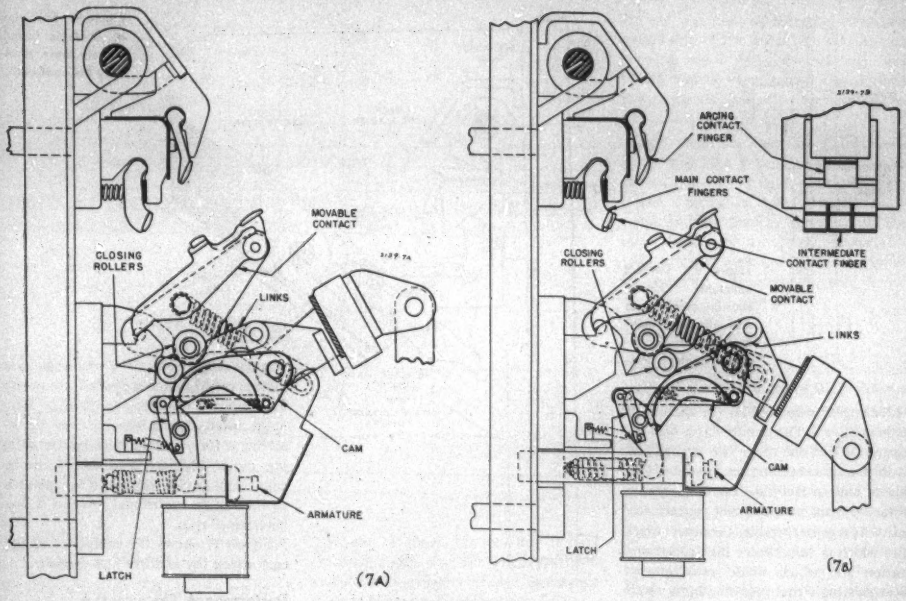

Figure 7A and B. Side views of breaker mechanism and contacts in open and collapsed positions

shown in Figure 6. Inasmuch as satisfactory performance was obtained at this rate of current rise, which is considerably above the rate of current rise obtainable in practice in d-c circuits, the design of the tripping mechanism was considered acceptable.

Breaker Structure

The tripping device just described was mounted on a breaker of conventional structure during the tests in the high-current circuit, both as a convenient method for testing the device itself, and also to observe the effects of high-speed operation on the mechanisms usually associated with more or less conventional circuit breakers.

As a result of these observations a novel breaker structure was evolved. Figure 7A illustrates the mechanism and contact arrangement designed for the application, with the mechanism reset ready to close. Positioned before the armature is a rotative latch normally supporting a cam-shaped member. The cam is so shaped that drawing a roller over its surface, by means of lever-actuated links, causes the movable contact to move to the fully closed position. Opening is equally simple to accomplish. Releasing the armature (Figure 7A) causes the latch to rotate from under the cam. The cam, closing rollers, and movable contact then collapse simultaneously. The opening speed is thereby dependent only on the applied opening force. Toggles with their hard-to-accelerate characteristics, under normal usage, are entirely eliminated. This mechanism represents a considerable departure from the usual toggle-activated circuit-breaker mechanism which does not lend itself so well to high-speed operation and is responsible to a considerable degree for the high-speed opening performance obtained with this new circuit breaker.

The contact arrangement designed for this high-speed breaker represents a considerable advance in the art of circuit-breaker design. Bearing in mind that it was considered desirable to design a breaker which would successfully withstand any tendency to blow open on currents of high magnitude in the forward or normal direction, it was decided to advantageously use the magnetic forces rather than to resort to brute force which would lead to a massive hard-to-accelerate structure. To this end the contacts were arranged so that the magnetic forces would add to the contact pressure rather than subtract from it.

Figure 8 shows that all points of contact are beneficially affected by the magnetic forces. The path of the current at the arcing contacts, main contact fingers, and at the lower end of the movable bridging contact is reversed sufficiently to "Magne-seal" then closed against currents of high magnitude and to gain equally from the accelerating effect of the magnetic forces when the restraint of the operating mechanism is removed.

Several other advantages accrued from this contact construction other than those listed above. A one-piece relatively light movable contact member was obtained which permitted the accomplishing of the high-speed operation objective. The pivoting of the lower end of this contact member on a fixed point on the lower stud permitted the eliminating of a heavy flexible connection which would otherwise have been mandatory. The difficulties experienced in designing adequate life into heavy braids capable of carrying currents in the order of 1,600 amperes with reasonable temperature limits and in overcoming their inherent resistance to angular movement are well known. The mounting of the arcing and main contacts on the upper stud resulted in light low-inertia parts which solved the problem of obtaining proper contact sequence between the primary and secondary circuits. Proper contact sequence is especially difficult to obtain with high-speed operation if the parts involved in the sequence are of relatively high inertia.

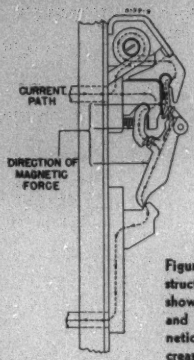

Figure 8. Contact structure closed showing current path and effect of magnetic forces to increase contact pressure

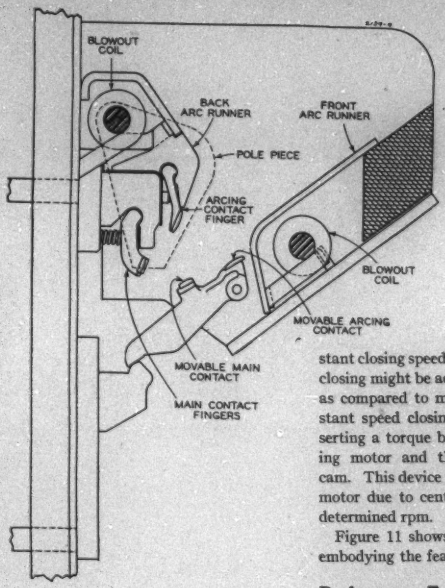

Figure 9. Side view of contacts (open) and arc chute, showing blowout coils

Three fingers were used for the stationary main contact. The middle finger was arranged to lead the other two slightly, so as to minimize burning on the other two fingers and to facilitate current transfer from the main to the arcing contact circuit. As a general result, a contact structure which is suitable for high-speed operation and which would satisfactorily meet existing switchgear standards as to temperature rise and reliability was obtained. Since electrochemical processes generally signify continuous full-current operation, this new contact structure for high-speed breakers provides a practical answer to continuity of service, by virtue of having both main and arcing contacts, generally considered necessary for continuous low-temperature-rise operation.

Current-Interrupting Device

The current-interrupting device designed for this breaker is extremely simple in construction and in operation. Figure 9 is a side view showing the component parts. The interrupting unit consists of a simple open-type arc chute and two blowout coils. One coil is in series with the arcing contacts on the upper stud of the breaker. Associated with this coil is an iron core and two pole pieces of conventional construction which act upon the arc terminus on the arc runner and the arc proper. The other coil is in series with arc runner located over the movable contact. This coil has only an iron core (no pole piece) which acts only on the arc terminus when it strikes the arc runner.

Successful operation is based entirely on rapidly increasing the length of the arc, therefore, the resistance, to the point where extinguishment takes place. Evidence of the effectiveness of this simple chute is shown in Figure 10. From current peak to zero is a smooth unbroken line descending at a rapid rate, an excellent illustration of efficient current interruption. The advantage of this type of chute is that, having been designed for a specific voltage level, it has no current limitation. Any increase in current merely increases the magnetic forces which in turn speed interruption.

Closing Drive

Since rectifier anodes are operated in groups of six or multiples of six, it was decided that six individual breaker poles, each with its independent current directional trip, would be mounted on a common panel. A motor-driven closing mechanism was selected as the most suitable means for obtaining reliable closing performance. This mechanism consisted of a series motor suitable for either a-c or d-c operation, a torque brake, and a gear-driven closing cam. This complete unit was connected to a closing crossbar affixed to the closing lever of each individual pole. Operating the closing crossbar through 360 degrees of cam travel would cause any number of poles in the open position to be closed. This was particularly desirable since on arc-back with high-speed breaker operation, the arc-back is removed before all anodes feeding into the rectifier are caused to arc back. Since under this condition the closing load on the motor drive can vary widely, it was desirable to obtain a relatively constant closing speed. Otherwise single-pole closing might be accomplished too rapidly as compared to multipole closing. Constant speed closing was obtained by inserting a torque brake between the driving motor and the gear-driven closing cam. This device functioned to brake the motor due to centrifugal force at a predetermined rpm.

Figure 11 shows the completed design embodying the features just described.

Performance Tests on the High-Speed Anode Breaker

Factory Tests

During the progress of development of this new high-speed anode air circuit breaker, several representative short-circuit tests were made in the factory testing department. After the final design had been reached a complete six-pole model was built and tested in a rectifier circuit in the factory. Figure 12 indicates the test arrangements made and power circuits used.

Results of these tests were gratifying, but it was realized that the test conditions imposed might not be so severe as would be encountered in the field, especially for large electrochemical pot lines. The rectifier transformer used during these tests and the a-c system capacity were such that current contributions from other anodes in the same rectifier which fed into the anode in arc-back were as high as would be usually encountered in the field. However, it was impossible to duplicate d-c contributions from parallel rectifiers such as would be encountered in large electrochemical installations. Instead, an 1,800-kw 600-volt motor-generator set was connected to the same bus, but this unit lacked capacity for such large d-c contributions as were anticipated in the field. It also required its own high-speed breaker protection to prevent commutator damage, so that the duration of

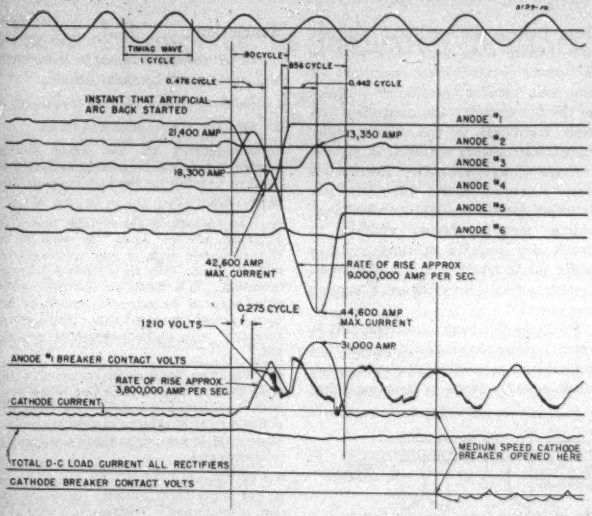

Figure 10. Typical oscillogram taken during field tests

its current contribution to the arc-back was limited.

Field Tests

Therefore, it was felt advisable to confirm final factory tests by making operating-speed and interrupting-capacity tests in a large rectifier installation. Arrangements were made for such tests. This rectifier installation consisted of eight 650-volt 2,600-kw rectifiers, supplied from four rectifier transformers, all connected to the same d-c bus. Short-circuit capacity at the 13.8-kv a-c supply bus was approximately 400,000 kva. D-c load during the test period averaged 20,800 kw on the eight rectifiers.

Figure 13 shows the one-line power-circuit diagram for the eight rectifiers and test arrangements for the rectifier and six-pole high-speed anode circuit breaker. Two six-element oscillographs were used to record current and voltage behavior in the various circuits simultaneously.

Since arc-backs cannot be produced at a predictable instant, it is necessary to simulate an arc-back by short-circuiting one rectifier element with a switch at the desired instant. Such a method imposes short-circuit currents which exceed the values reached under natural arc-back conditions, because they eliminate the effect of arc drop in the rectifier element in arc-back. Thus such test conditions are in error in the conservative direction. A large electrically operated power circuit breaker was used as the short-circuiting switch during the tests. No overcurrent tripping action was provided with this switch and so it remained closed until it was opened manually after each short-circuit test was conducted.

This particular installation had been made with the cathode switching-type arc-back protective equipment on all rectifiers. During the tests the regular high-speed cathode breaker remained in the open position at all times. A suitable 4,000-ampere medium-speed air circuit breaker with overcurrent tripping device was substituted instead.

Oscillographic Results

Figure 10 is a reproduction of an actual oscillogram obtained during the field tests. Several such oscillograms were taken, and this particular one is typical of the maximum fault conditions recorded.

Trace for anode 1 shows the current through the short-circuiting switch. It is apparent that the instant of switch closure occurred during the time of normal forward-current conduction for anode 1. Performance of pole 1 of the high-speed anode circuit breaker is clearly indicated on the oscillogram. Maximum current contributions come from anodes 1 and 5 and from the other paralleled rectifiers through the cathode line.

An interesting piece of incidental data obtained in this test is the record of the natural arc-back in anode 5. After its high forward-current contribution, it immediately went into arc-back as proved by the reversal of current. Performance

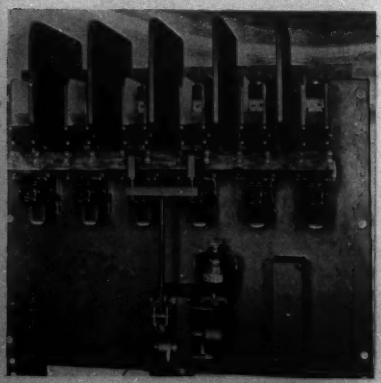

Figure 11 (left). The new high-speed breaker

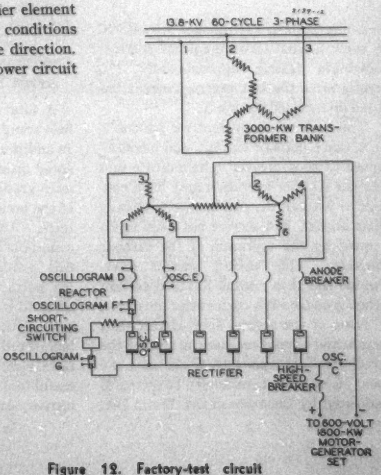

Figure 12. Factory-test circuit

of pole 5 is clearly indicated by the current trace for that anode.

Time required for contacts of pole 1 to part after current reversal was 0.275 cycle as measured by the trace of "anode 1 breaker contact volts." Current reduction as a result of arc quenching in the arc chute always started appreciably earlier than one-half cycle, according to the oscillograms taken during each test. The values of 0.476 cycle and 0.442 cycle illustrated in Figure 10 were typical.

Study of the cathode-current behavior shows that the individual poles each contributed interrupting effort, not only to that of the currents from the other anodes, but also to those from other rectifiers as well. In fact, pole 5 successfully interrupted all contributions. This is proved, because the traces for anodes 2, 3, 4, and 6 show normal forward-current rectifier operation lasting approximately $1^1/_4$ cycles after the last reverse current has been interrupted by pole 5.

Traces of anode current for anodes 2, 3, 4, and 6 cathode current, and medium-speed cathode-breaker volts indicate that regular rectifier operation may have continued without distress on the remaining four anodes, had service not been interrupted by the operation of the cathode breaker. This circuit breaker interrupted less than normal full-load current when it opened $2^1/_2$ cycles after the event.

None of the several short-circuit tests conducted caused arc-back in any of the other rectifiers connected to the same d-c bus. Evidence of continuity of service is indicated by the trace of the "Total D-C Load Current All Rectifiers" in Figure 10. During these tests there were no a-c power circuit-breaker operations for the main rectifier transformer included in the test circuit. The companion rectifier connected to the same rectifier transformer always remained in service.

Surge-voltage recording instruments were connected across the interphase transformer and anode to neutral low-voltage main-transformer windings to detect any evidence of surge voltages which might result from the high-speed breaker action. No evidence of surging was recorded.

Oscillographic tests were conducted to determine the time required to interrupt normal load on the rectifier when tripping all six poles by means of removing polarizing coil voltage. Approximately $1^1/_2$ cycles were required after the switch in the polarizing circuit was opened.

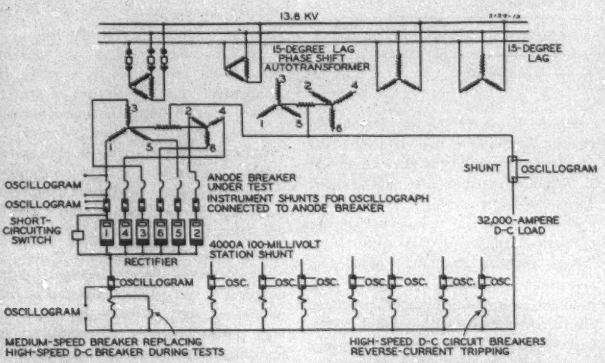

Figure 13. Field-test circuit

Condition of Anode Circuit Breaker After Tests

A total of six tests were made in the field using the circuit shown in Figure 13. In addition to obtaining satisfactory high-speed operation, the results were particularly gratifying, in view of the condition of the breaker after the completion of the tests. The contacts were in excellent condition and justified the adoption of this arrangement for commercial use. No parts would have required replacement to continue in service. The condition of the breaker after tests and the high-speed performance obtained during tests clearly indicated that a new and useful tool had been provided to cope with mercury-arc rectifier arc-backs.

Conclusion

The advantages obtained by using such high-speed anode breakers include:

1. Shock to the transformer is reduced.
2. Shock to the rectifier is reduced.
3. Maintenance on a-c power circuit breaker is reduced, because it no longer is required to interrupt the high currents due to arc-back.
4. The vacuum in the rectifier is not so adversely affected when the arc-back is limited to one cycle or less, as compared with the longer time for a-c power-breaker operation. This means any rectifier which arcs back can be returned to service at once, whereas time out for pumping is often necessary with cathode-switching protection.
5. When two rectifiers are connected to the same transformer, only the one which arcs back is subjected to outage. The other remains in service. This has a most important bearing on improved continuity of service in many cases.
6. Likelihood of simultaneous arc-backs or spread of arc-backs to other parallel rectifiers is minimized. The reason is that the short circuit on the d-c bus is removed in one cycle or less. Again continuity of service is improved.
7. The anode breakers are useful disconnecting devices when two rectifiers are fed from a single transformer. They lend themselves to the isolating of one rectifier for maintenance or repair work without interrupting operation on the other rectifier.
8. High overcurrent duty is confined to one device for the anode-switching arrangement, whereas with cathode switching both cathode switch and a-c power circuit breaker open under high duty requirements. Maintenance is thus reduced.
9. Since each pole of the six-pole anode breaker opens independently of the other poles, and each pole is equipped with an operation counter, a record is provided of the anode arc-backs. This often is advantageous in locating and correcting arc-back trouble.

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Field Harmonics in Induction Motors

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I. Introduction

ABOUT 40 papers have been written on the asynchronous torques, synchronous cusps at running, synchronous cusps at standstill (dead points), and noise of the induction motor. The subject has been also treated in some textbooks.* My aim is to give a coherent representation of the harmonic problem in induction motors. It is based on the work of my predecessors, on my own work, and on my experience.

It is intended to give not only a physical explanation of the phenomena but also to determine them quantitatively, that is, to determine the magnitudes of the different forces which produce the noise as well as of the different torques which influence the torque-speed curve. An exact knowledge of the currents produced by the field harmonics in the rotor is necessary for solving this problem. Since the magnitude of the harmonic currents in the rotor depends on the rotor leakage, a special study of the leakage of the single harmonics will be necessary. Of great influence is here the differential leakage; its amount increases with the order of the harmonic and therefore becomes important for the slot harmonics.

Thus a complete representation of the harmonic problem in induction motors involves the following topics:

1. The harmonics of the stator, their amplitudes, and their speed with regard to the stator and rotor.
2. The harmonics of the rotor, their amplitudes, and their speed with regard to the stator and rotor.
3. The force waves produced by the harmonics and their frequencies.
4. The resistance and reactance of the rotor with regard to the different harmonics.
5. The rotor currents produced by the different harmonics.
6. The forces produced by the harmonics.
7. The asynchronous torques.
8. The synchronous torques during running and at standstill.
9. Means to avoid the noise and the parasitic torques.

It is intended to divide the representation in three parts. This paper contains the topics 1, 2, and 3, that is, it treats the noise problem qualitatively. The magnitude of the forces that produce the noise will be determined in the third part, when the resistance and reactance of the rotor with regard to the different harmonics have been discussed in the second part.

II. The Stator and Rotor Harmonics

Since not only the windings with an integral number of slots per pole per phase are considered, but the windings with a fractional number of slots as well, it becomes expedient to take as the "fundamental" harmonic the wave, the length of which is equal to the circumference of the stator bore. The synchronous wave will be then the harmonic of the order $n' = p$; this is the "main" or "synchronous" harmonic. If in the case when the number of slots per pole per phase is an integer, it is desirable to use the main harmonic as the fundamental, the ratio $n = n'/p$ is valid; n is then the order of the harmonic with regard to the synchronous wave.

As shown in appendix 1, the order as well as the direction of rotation of the stator harmonics is defined by the two equations

$$\left(\frac{n'}{p}+1\right)\frac{\beta}{2}=k \tag{1}$$

$$\left(\frac{n'}{p}\mp 1\right)\frac{\beta}{2m_1}=k_1 \tag{2}$$

where k is an integer excluding 0, k_1 an integer including 0. When the minus sign in equation 2 is used, n' travels with the synchronous harmonic; when the plus sign in equation 2 is used, n' travels opposite to the synchronous harmonic.

When the number of slots per pole per phase q_1 is an integer, β has to be set in equations 1 and 2 equal to 2, whence

$$n'=(k_1m_1+1)P \tag{3}$$

or

$$n=k_1m_1+1 \tag{4}$$

where k_1 is any positive or negative integer including 0. When q_1 is an integer, and the winding is a symmetrical three-phase 60-degree phase belt winding, k_1 is a positive or negative even integer including 0. When n' is positive, the harmonic travels with the synchronous harmonic; when n' is negative, the harmonic travels opposite to the synchronous harmonic.

In appendix 1, it is further shown that the n' harmonic of the stator produces the following rotor harmonics

$$m'=k_2Q_2+n' \text{ for the squirrel-cage rotor} \tag{5}$$

$$m'=k_2pm_2+n' \text{ for the wound rotor with } q_2 \text{ an integer} \tag{6}$$

where k_2 is a positive as well as a negative integer including 0. For positive values of the slip s_n' the harmonic m' travels with the rotor when m' is positive, opposite to the rotor when m' is negative.

The stator slot harmonics are given by the equation

$$n_{s1}'=\pm Q_1+p \tag{7}$$

and the rotor slot harmonics by the equation

$$m_{s1}'=\pm Q_2+p \tag{8}$$

It follows from equations 5, 6, and 8 that the rotor slot harmonics are produced by the main (synchronous) wave of the stator, and that $k_2 = \pm 1$ corresponds to the slot harmonics of the squirrel-cage rotor, while a large k_2 corresponds to the slot harmonics of the wound rotor.

Equation 6 assumes that the number of slots per pole per phase q_2 of the rotor is an integer. If q_2 is a fractional number, $k_2\frac{2}{\beta_2}pm_2$ has to be inserted in equation 6 instead of k_2pm_2 (corresponding to equation 34, appendix 1). This is valid also for the formulas derived from equation 6 in the following.

In appendix 2 formulas are given for the harmonics of the magnetomotive forces of the stator and rotor which take into account their speed relative to the stator as well as to the rotor. Since the noise problem only is considered here, the magnetomotive forces with regard to the stator are of importance.

The magnetomotive force of the n'th stator harmonic is

$$b_{n'}=B_{n'}\sin\left(\omega t-n'\frac{\pi}{p\tau}x_1\right) \tag{9}$$

and the magnetomotive force of the m'th rotor harmonic

$$b_{m'}=B_{m'}\sin\left[\left(1+\frac{m'-n'}{p}(1-s)\right)\times\omega t-m'\frac{\pi}{p\tau}x_1\right] \tag{10}$$

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* The fundamental paper on the influence of harmonics in the squirrel cage rotor has been published by L. Dreyfus.[16] The most detailed representation is given in the textbook of R. Richter, ELEKTRISCHE MASCHINEN.[10]

The rotor harmonic m' is produced by the stator harmonic n'; therefore, corresponding to the equations 5 and 6

$$b_{m'}=B_{m'}\sin\left[\left(1+\frac{k_2Q_2}{p}(1-s)\right)\times\omega t-m'\frac{\pi}{p_T}x_1\right]$$ for the squirrel-cage rotor (10a)

$$b_{m'}=B_{m'}\sin\left[(1+k_2m_2(1-s))\omega t-m'\frac{\pi}{p_T}x_1\right]$$ for the wound rotor (10b)

The values of $B_{n'}$ and $B_{m'}$ are given in appendix 2.

III. The Force Waves and Their Frequencies

The driving force of the machine is a tangential force produced by the main flux wave and the main magnetomotive force wave. The flux harmonics and the harmonics of the magnetomotive force produce parasitic tangential forces which contribute to the noise. However, the main source of noise is the group of radial forces produced by the flux harmonics. The radial force that corresponds to the induction b in the gap is

$$f_r=1.385b^2\times10^{-8}\text{ pounds per square inch}$$

b consists of all stator and rotor harmonics. Hence b^2 is the sum of the squares of all stator and rotor harmonics plus twice the product of each stator harmonic with each other stator harmonic, of each rotor harmonic with each other rotor harmonic and of each stator harmonic with each rotor harmonic. We write in general form

$$f_r=b_\gamma\cdot b_{\mu'}$$

We can use this formula for all five components of b^2 making γ' and μ' equal to the values of n' and m' in consideration. It is in general

$$b_{\gamma'}=B_{\gamma'}\sin\left(\omega_{\gamma'}t-\gamma'\frac{\pi}{p_T}x_1\right)$$

$$b_{\mu'}=B_{\mu'}\sin\left(\omega_{\mu'}t-\mu'\frac{\pi}{p_T}x_1\right)$$

so that

$$f_r=b_\gamma\cdot b_\mu=\frac{1}{2}B'B_{\mu'}\times\cos\left[(\omega_{\gamma'}-\omega_{\mu'})t-(\gamma'-\mu')\frac{\pi}{p_T}x_1\right]-\frac{1}{2}B_{\gamma'}B_{\mu'}\cos\left[(\omega_{\gamma'}+\omega_{\mu'})t-(\gamma'+\mu')\frac{\pi}{p_T}x_1\right]$$ (11)

Thus the radial force f_r consists of two force waves, one having $\gamma'-\mu'$ force pole pairs and the frequency $\omega_{\gamma'}-\omega_{\mu'}$ the other having $\gamma'+\mu'$ force pole pairs and the frequency $\omega_{\gamma'}+\omega_{\mu'}$. We designate the number of force pole pairs by k. $k=0$ is a stationary pulsating force, $k=1$ is a force wave with two poles, $k=2$ is a force wave with four poles, and so on. The larger the value of k, the shorter is the wave length. The stator is, in general, stiffer to short wave distortion (k large) than to large wave distortion (k small). Yet, depending on the construction of the machine, the small wave distortion may be dangerous as well.

We consider now the different components of b^2.

(*a*). *Stator harmonics only.* In equation 11 we have to insert $\gamma'=n_a'$, $\mu'=n_b'$

It follows further from equation 9

$$\omega_{\gamma'}=\omega_{\mu'}=\omega=2\pi f_1$$

Thus

$$k=n_a'+n_b' \quad f_+=2f_1$$
$$k=n_a'-n_b' \quad f_-=0$$ (12)

f_+ is the frequency of the force wave, when the sum of n_a' and n_b' is taken; f_- is the frequency of the force wave, when the difference of n_a' and n_b' is taken. n_a' and n_b' can be positive as well as negative.

When a single stator wave is considered, then $n_b'=n_a'$ and

$$k=2n_a' \quad f_+=2f_1$$ (12a)

Thus the force waves produced by the stator harmonics have double the line frequency. Also the main harmonic produces a force wave of double the line frequency.

The consideration of the case $k=1$, which must be avoided, we limit for the sake of clearness to integral values of q_1, since fractional numbers of q_1 are not often used in induction motors. $k=1$ means

$$n_a'+n_b'=\pm1 \text{ or } n_a'-n_b'=\pm1$$

With equation 3 this gives

$$n_a'+n_b'=[(k_{1a}+k_{1b})m_1+2]p=\pm1$$
$$n_a'-n_b'=(k_{1a}-k_{1b})m_1p=\pm1$$

Since k is a positive or a negative integer including 0, the case $n_a'+n_b'=\pm1$ cannot occur. $n_a'-n_b'=\pm1$ is possible only when $p=1$, $m_1=1$ and k_{1a} or k_{1b} is an odd number, that is, when the magnetomotive force contains even harmonics.

(*b*). *Rotor harmonics only.* In this case $\gamma=m_a'$, $\mu=m_b'$. It follows further from equation 10

$$b_{m_a'}=B_{m_b'}\sin\left[\left(1+\frac{m_a'-n_a'}{p}(1-s)\right)\times\omega t-m_a'\frac{\pi}{p_T}x_1\right]$$

$$b_{m_b'}=B_{m_b'}\sin\left[\left(1+\frac{m_b'-n_b'}{p}(1-s)\right)\times\omega t-m_b'\frac{\pi}{p_T}x_1\right]$$

Inserting here equation 6, we find for the wound rotor with q_2 integral

$$k=m_a'+m_b' \quad f_+=[2+(k_{2a}+k_{2b})\times m_2(1-s)]f_1$$
$$k=m_a'-m_b' \quad f_-=[(k_{2a}-k_{2b})m_2(1-s)]f_1$$ (13)

and inserting equation 5, we find for the squirrel-cage rotor

$$k=m_a'+m_b' \quad f_+=\left[2+(k_{2a}+k_{2b})\frac{Q_2}{p}(1-s)\right]f_1$$
$$k=m_a'-m_b' \quad f_-=\left[(k_{2a}-k_{2b})\frac{Q_2}{p}(1-s)\right]f_1$$ (14)

m_a', m_b', k_{2a}, and k_{2b} in equations 13 and 14 can be positive as well as negative.

For the case of the squirrel-cage motor as shown in appendix 2, the value of $B_{m'}$ becomes smaller, the larger the value of k_2. $k_2=\pm1$ gives the largest amplitude for the rotor harmonic. Considering this case, that is,

$$k_{2a}=\pm1 \quad k_{2b}=\pm1$$

we find for the squirrel-cage rotor

$$f_+=\left[1\pm\frac{Q_2}{p}(1-s)\right]2f_1$$
$$f_-=0$$ (13a)

when k_{2a} and k_{2b} have the same sign and

$$f_+=2f_1$$
$$f_-=\frac{Q_2}{p}(1-s)2f_1$$ (13b)

when k_{2a} and k_{2b} have different signs.

When a single harmonic is considered, then $m_a'=m_b'$; $k_{2a}=k_{2b}=k_2$

$$k=2\mu_a' \quad f=\left[1+k_2\frac{Q_2}{p}(1-s)\right]2f_1$$ (13c)

m_2 instead of Q_2/p is to be inserted in this equation for the wound rotor.

If we limit again the consideration of the case $k=1$ to q_1 integral there will be

$$m_a'+m_b'=\pm1$$

or

$$m_a'-m_b'=\pm1$$

With equations 3 and 5, this gives for the squirrel-cage rotor

$$m_a'+m_b'=\pm1=(k_{2a}+k_{2b})Q_2+[(k_{1a}+k_{1b})m_1+2]p$$

k_{2a} and k_{2b} are positive or negative integers including 0. In the usual case of a 60-degree-phase-belt winding, k_{1a} and k_{1b} are even integers including 0. Only the 120-degree-phase-belt winding, (two speed motors) may have even values as well as odd values of k_1. In order that $n_a'+n_b'=\pm 1$, the equation must be satisfied.

$$(k_{2a}+k_{2b})Q_2=-(k_{1a}+k_{1b})m_1p-2p\mp 1$$

With k_{1a} and k_{1b} even integers, this is possible only when Q_2 is an odd number. For $n_a'-n_b'=\pm 1$ it follows that

$$n_a'-n_b'=\pm 1=(k_{2a}-k_{2b})Q_2+(k_{1a}-k_{1b})m_1p$$

or

$$(k_{2a}-k_{2b})Q_2=(k_{1a}-k_{1b})m_1p\mp 1$$

With k_{1a} and k_{1b} even integers this equation can be satisfied when Q_2 is an odd number. Thus the rotor harmonics produce $k=1$ (two-pole force waves) when Q_2 is an odd number. When the stator winding produces even harmonics (120-degree-phase-belt winding) also an even Q_2 may produce $k=1$. The wound rotor has usually $q_2=$integer and Q_2 an even number. In the case $q_2=$fractional number, the equation 3 and equation 34, appendix 1, have to be used in order to find whether or not $k=1$ is possible.

The value $\frac{Qn}{60}=\frac{Qf}{p}$ is the slot frequency. It follows from equations 13a and 13b that the frequency of the noise which the rotor harmonics produce is approximately equal to double the slot frequency or to double the line frequency. Seldom another frequency corresponding to equation 13 may occur.

(c). *Products of stator and rotor harmonics.* Here

$$\gamma'=n_b' \qquad \mu'=m_a'$$

m_a' is produced by the stator harmonic n_a'. From equations 9 and 10 we get for the squirrel-cage rotor

$$\left.\begin{aligned} k=n_b'+m_a' \quad f_+&=\left[2+K_{2a}\frac{Q_2}{p}(1-s)\right]f_1\\ k=n_b'-m_a' \quad f_-&=\left[K_{2a}\frac{Q_2}{p}(1-s)\right]f_1\end{aligned}\right\} \quad (15)$$

In this equation m_2 is to be substituted for $\frac{Q_2}{p}$ for the wound rotor with q_2 equal to an integer.

It follows from equation 15 that the frequency of the force waves produced by stator harmonics in co-operation with rotor harmonics does not depend on the order of the stator harmonic; it depends on the factor k_2 and also on the number of rotor phases, if the rotor is a wound rotor, or on the number of rotor slots, if the rotor is of squirrel-cage type.

When $k_{2a}=0$, m_a' is equal to n_a' and there will be

$$\left.\begin{aligned} k=n_b'+m_a' \quad f_+&=2f_1\\ k=n_b'-m_a' \quad f_-&=0\end{aligned}\right\} \quad (15a)$$

For the rotor slot harmonics of the squirrel cage, $k_{2a}=\pm 1$. Thus, when the rotor slot harmonics are involved, the frequencies of the force waves of the squirrel-cage rotor are

$$\left.\begin{aligned} k=n_b'+m_a' \quad f_+&=\left[2\pm\frac{Q_2}{p}(1-s)\right]f_1\\ k=n_b'-m_a' \quad f_-&=\frac{Q_2}{p}(1-s)f_1\end{aligned}\right\} \quad (15b)$$

It follows from equations 7 and 8 for the co-operation of the stator slot harmonics with the rotor slot harmonics

$$k_{s1}=n_{s1}'+m_{s1}'=\pm Q_1+p=Q_2+p$$

and

$$k_{s1}=n_{s1}'-m_{s1}'=\pm Q_1\mp Q_2$$

The smallest absolute values of k_{s1} are

$$\left.\begin{aligned} k_{s1}&=Q_1-Q_2=2p\\ k_{s1}&=Q_1-Q_2\end{aligned}\right\} \quad (16)$$

Disturbing noise can be expected, when k_{s1} as given by equation 16 is a small number. $k_{s1}=1$ is dangerous, but under certain conditions even $k_{s1}=20$ may not be permissible. The noise produced by the machine depends not only on the harmonics and the radial forces produced by them, it depends also on the mechanical construction of the machine and on the number of poles which determines the depth of the stator core.

When the stator harmonics co-operate with rotor harmonics, the case $k=1$ results in

$$n_b'+m_a'=\pm 1$$

or

$$n_b'-m_a'=\pm 1$$

With equations 3 and 5, this gives for the squirrel-cage rotor (q_1 is an integer)

$$n_b'+m_a'=\pm 1=[(k_{1a}+k_{1b})m_1+2]p+k_{2a}Q_2$$

$$n_b'-m_a'=\pm 1=(k_{1b}-k_{1a})m_1p-k_{2a}Q_2$$

Applying here the same considerations as in the case of two rotor harmonics, treated under (b), we find the same results as there, namely that $k=1$ occurs when Q_2 is an odd number.

It follows from equations 15a and 15b that the frequency of the force waves of a squirrel-cage motor which are produced through the co-operation of the stator and rotor harmonics have approximately the slot frequency or double the line frequency. Occasionally higher frequencies corresponding to equation 15 may occur.

Since equation 8 is valid also for the wound rotor, the results derived for the squirrel-cage motor are valid also for the wound-rotor motor.

(d). *Zero-pole forces* ($k=0$). Under special circumstances the case $k=0$ may cause considerable trouble. $k=0$ means that there are no force poles, that the force is constant around the stator bore at any instant, but that it changes its value with the frequency $\omega_{\gamma'}-\omega_{\mu'}$ or $\omega_{\gamma'}+\omega_{\mu'}$ (equation 11). It can be seen from this equation and from the considerations under (a) and (b) that $k=0$ is possible only when stator harmonics co-operate with rotor harmonics; then we have $\omega_{\gamma'}-\omega_{\mu'}\neq 0$ and also $\omega_{\gamma'}+\omega_{\mu'}\neq 0$

Referring to (c) we have

$$\gamma'=n_b' \qquad \mu'=m_a'$$

and from equations 3 and 6 for the wound rotor

$$k=n_b'+m_a'=0=(k_{1b}+k_{1a})m_1+2+k_{2a}m_2$$

$$k=n_b'-m_a'=0=(k_{1b}-k_{1a})m_1-k_{2a}m_2$$

The number of phases of the rotor m_2 is usually equal to three. Thus $k=n_b'+m_a'$ will be equal to 0, when

$$(k_{1b}+k_{1a})\frac{m_1}{3}+\frac{2}{3}=-k_{2a}$$

that is, the sum $n_b'+m_a'$ cannot produce $k=0$, if the stator has $m_1=3$. $k=n_b'-m_a'$ will be equal to 0, when

$$(k_{1b}-k_{1a})\frac{m_1}{3}=k_{2a} \quad (17a)$$

If the stator has a three-phase winding there will be in this case, many combinations which will give $k=0$. The frequency of the force is given by equation 15 when m_2 is substituted for Q_2/p. The equation 15 is independent of the value of k.

We consider for example, the combination (q_1 integral)

$$m_1=m_2=3 \quad k_{1a}=0 \quad k_{1b}=-2=k_{2a}$$

To $k_{1a}=0$ corresponds $n_a'=p$; to $k_{1b}=-2$ corresponds $n_b'=-5p$; to $k_{2a}=-2$ corresponds $m_a'=-6p+p=-5p$ and $n_b'-m_a'=0$. The frequency of the stationary force produced by $n_b'=-5p$ and $m_a'=-5p$ is (equation 15)

$$f_-=-2\times 3(1-s)f_1=360(1-s) \text{ cycles per second}$$

If we would consider the combination $k_{1a}=0$, $k_{1b}=-4=k_{2a}$, that is, $n_a'=p$, $n_b'=-11p$, $m_a'=-11p$, we would find that

the stationary force oscillates with 720 $(1-s)$ cycles per second.

For the squirrel-cage rotor we find from equations 3 and 5

$$k=n_b'+m_a'=0=[(k_{1b}+k_{1a})m_1+2]p+k_{2a}Q$$
$$k=n_b'-m_a'=0=(k_{1b}-k_{1a})m_1p-k_{2a}Q_2$$

Since k_{1a} and k_{1b} are integers, $k=0$ will occur here when

$$\left.\begin{array}{l}\dfrac{k_{2a}Q_2}{p} \text{ is an integer or}\\[2ex] \dfrac{k_{2a}Q_2}{m_1p} \text{ is an integer}\end{array}\right\} \quad (17b)$$

The frequency of the forces is given by equation 15 which is independent of the value of k.

The equation 17a for the wound rotor can be satisfied by small values of k_{1a}, k_{1b}, and k_{2a}. The corresponding field amplitudes as well as the $k=0$ force will therefore be considerable. To the equation 17b corresponds usually a relatively large value of k_{2a} or k_{1b} or k_{1a}, that is, a harmonic with small amplitude. This is the reason why $k=0$ may more often make trouble in a machine with a wound rotor than in a machine with a squirrel-cage rotor.

The natural frequency of a stator core for radial vibrations is approximately

$$f_{\text{rad. vib.}}=\frac{32.4\times10^3}{r}\sqrt{\frac{1}{1+h_t/h_c}} \text{ cycles per second} \quad (18)$$

where r is the radius in the middle of the core, h_t the depth of the tooth and h_c the depth of the core. It depends mainly on the radius of the core.

Influence of Saturation

For the stator harmonics (equation 37, appendix 2) is valid.

$$b_{n'}=B_{n'}\sin\left(\omega t-n'\frac{\pi}{p\tau}x_1\right)$$

Since all harmonics n' are produced by the same current, ω is common for all harmonics, and each harmonic travels exactly its wave length during one cycle of the current.

If the magnetic circuit is saturated, the main harmonic of the magnetomotive force produces, besides the main field harmonic, also saturation field harmonics which travel 3, 5, ... wave lengths when the main harmonic travels only one wave length. The saturation harmonics are bound to the main harmonic and travel with it without changing position with regard to each other. For these harmonics we have to write

$$b_\gamma=B_\gamma\sin\left(\gamma\omega t-\gamma\frac{\pi}{\tau}x_1\right) \quad \gamma=3,\ 5,\ \ldots . \quad (19)$$

The saturation harmonics produce in cooperation with the rotor harmonics, force waves, the frequencies of which can be found from equations 11, 10, and 18 as follows

$$\left.\begin{array}{ll} & \gamma_b'=3 \quad f_+=\left[4+\dfrac{m_a'-n_a'}{p}(1-s)\right]f_1\\ k=\gamma_b'+m_a' & \\ & \gamma_b'=5 \quad f_+=\left[6+\dfrac{m_a'-n_a'}{p}(1-s)\right]f_1\\ & \gamma_b'=3 \quad f_-=\left[2-\dfrac{m_a'-n_a'}{p}(1-s)\right]f_1\\ k=\gamma_b'-m_a' & \\ & \gamma_b'=5 \quad f_-=\left[4-\dfrac{m_a'-n_a'}{p}(1-s)\right]f_1\end{array}\right\} \quad (20)$$

The difference $m_a'-n_a'$ is given for the wound rotor as well as for the squirrel-cage rotor, by equations 5, 6, and equation 34, appendix 1.

Appendix I. The Order of the Stator and Rotor Harmonics

(a) The Stator Harmonics

We consider a stator winding with a fractional number of slots per pole per phase. Since subharmonics are possible, we take as fundamental the wave, the length of which is equal to the complete developed armature, that is, to 2π. The harmonic $n'=p$ is then the main harmonic (the "synchronous" harmonic).

The stator may have m_1 phases. The n'th harmonic of the magnetomotive force of one of the phases which we designate by 0 is

$$f_{1n'}{}^0=F_{1n'}\sin\omega t\cos n'\frac{x_1}{p\tau}\pi \quad (21)$$

When the number of slots per pole per phase is

$$q_1=a+\frac{b}{\beta} \quad (22)$$

where a is an integer, b/β a fractional number, and b and β have not a common divisor, then the winding repeats itself after each β poles. The winding with $q_1=$ integer repeats itself after two poles. The time and space angle between two adjacent phases are for q_1 an integer $\dfrac{2\pi}{m_1}$ and $n'\dfrac{2\pi}{pm_1}$; correspondingly these angles are for q_1 a fractional number

$$\frac{\pi\beta}{m_1} \text{ and } n'\frac{\pi\beta}{pm_1}$$

The time and space angle between the phase designated by 0 and the cth phase are therefore for $q_1=$ fractional number

$$\frac{\pi\beta}{m_1}c \text{ and } n'\frac{\pi\beta}{pm_1}c$$

Thus the magnetomotive force of the cth phase is

$$f_{1n'}{}^c=F_{1n'}\sin\left(\omega t-\frac{\pi}{m_1}\beta c\right)\times\cos\left(n'\frac{x_1}{p\tau}\pi-n'\frac{\pi}{pm_1}\beta c\right) \quad (23)$$

or

$$f_{1n'}{}^c=\frac{1}{2}F_{1n'}\left\{\sin\left[\left(\omega t-n'\frac{x_1}{p\tau}\pi\right)+\left(\frac{n'}{p}-1\right)\frac{\pi}{m_1}\beta c\right]+\sin\left[\left(\omega t+n'\frac{x_1}{p\tau}\pi\right)-\left(\frac{n'}{p}+1\right)\frac{\pi}{m_1}\beta c\right]\right\} \quad (23a)$$

In order to find the resultant magnetomotive force we have to take the sum of all m_1 phases, that is, from $c=0$ to $c=m_1-1$. Thus

$$f_{1n'}=\frac{1}{2}F_{n'}\left\{\left[\sin\left(\omega t-n'\frac{x_1}{p\tau}\pi\right)\times\sum_{c=0}^{c=m_1-1}\cos\left(\frac{n'}{p}-1\right)\frac{\pi}{m_1}\beta c+\cos\left(\omega t-n'\frac{x_1}{p\tau}\pi\right)\times\sum_{c=0}^{c=m_1-1}\sin\left(\frac{n'}{p}-1\right)\frac{\pi}{m_1}\beta c\right]+\left[\sin\left(\omega t+n'\frac{x_1}{p\tau}\pi\right)\times\sum_{c=0}^{c=m_1-1}\cos\left(\frac{n'}{p}+1\right)\frac{\pi}{m_1}\beta c-\cos\left(\omega t+n'\frac{x_1}{p\tau}\pi\right)\sum_{c=0}^{c=m_1-1}\sin\left(\frac{n'}{p}+1\right)\frac{\pi}{m_1}\beta c\right]\right\} \quad (24)$$

The four sums we designate in turn by a, b, a_1, and b_1, and the angles in the round parenthesis by α and δ. We can write

$$f_{1n'}=\frac{1}{2}F_{n'}[(a\sin\alpha+b\cos\alpha)+(a_1\sin\delta-b_1\cos\delta)] \quad (25)$$

or

$$f_{1n'}=\frac{1}{2}F_{n'}\left[\sqrt{a^2+b^2}\sin(\alpha+\gamma_1)+\sqrt{a_1{}^2+b_1{}^2}\sin(\delta+\gamma_2)\right]$$
$$=\frac{1}{2}F_{n'}\sqrt{a^2+b^2}\sin\left(\omega t-n'\frac{x_1}{p\tau}\pi+\gamma_1\right)+\frac{1}{2}F_{n'}\sqrt{a_1{}^2+b_1{}^2}\sin\left(\omega t+n'\frac{x_1}{p\tau}\pi+\gamma_2\right) \quad (25a)$$

These are two waves traveling in different directions, and both of the same order n'. Since the stator currents produce from each harmonic only one wave, traveling with the synchronous harmonic or opposite to it, it follows that for some harmonics the sums a and b, for other harmonics the sums a_1 and b_1, must be equal to zero.

We assume that a given harmonic, for example the n'th harmonic, travels with the synchronous harmonic. Then for this harmonic the sums a_1 and b_1 must be equal to zero, while $\sqrt{a^2+b^2}$ must have a definite

value. It can be seen that this will occur when

$$\left(\frac{n'}{p}+1\right)\frac{\beta}{2}=k \quad k \text{ integer excluding } 0$$

and

$$\left(\frac{n'}{p}-1\right)\frac{\pi}{m_1}\beta=2\pi k_1 \quad k_1 \text{ integer including } 0$$

There will be

$$a=\sum_{c=0}^{c=m_1-1}\cos\left(\frac{n'}{p}-1\right)\frac{\pi}{m_1}\beta c$$
$$=\sum_{c=0}^{c=m_1-1}\cos\ k_1 2\pi c=m_1$$
$$b=\sum_{c=0}^{c=m_1-1}\sin\left(\frac{n'}{p}-1\right)\frac{\pi}{m_1}\beta c$$
$$=\sum_{c=0}^{c=m_1-1}\sin k_1 2\pi c=0$$
$$a_1=\sum_{c=0}^{c=m_1-1}\cos\left(\frac{n'}{p}+1\right)\frac{\pi}{m_1}\beta c$$
$$=\sum_{c=0}^{c=m_1-1}\cos k\frac{2\pi}{m_1}c=0$$
$$b_1=\sum_{c=0}^{c=m_1-1}\sin\left(\frac{n'}{p}+1\right)\frac{\pi}{m_1}\beta c$$
$$=\sum_{c=0}^{c=m_1-1}\sin k\frac{2\pi}{m_1}c=0$$

On the other hand, if we assume that a given harmonic travels opposite to the rotation, we find that when

$$\left(\frac{n'}{p}+1\right)\frac{\beta}{2}=k \quad k \text{ integer excluding } 0$$

$$\left(\frac{n'}{p}+1\right)\frac{\pi}{m_1}\beta=k_1 2\pi \quad k_1 \text{ integer including } 0$$

the sums a and b will be zero while $\sqrt{a_1^2+b_1^2}$ has a definite value. Thus

$$\left.\begin{aligned}\left(\frac{n'}{p}+1\right)\frac{\beta}{2}&=k \quad k \text{ integer excluding } 0\\ \left(\frac{n'}{p}\mp 1\right)\frac{\beta}{2m_1}&=k_1 \quad k_1 \text{ integer including } 0\end{aligned}\right\} \tag{26}$$

are the criterions for the existence of the n'th harmonic in the magnetomotive force. When the minus sign is used, the harmonic travels with the synchronous harmonic; when the plus sign is used, the harmonic travels opposite to the synchronous harmonic.

The first criterion is independent of m_1, it indicates the existence of the n'th harmonic in the magnetomotive force of a single phase; the second criterion indicates the existence of the nth harmonic in the magnetomotive force of the total winding.[12]

It follows from the preceding that with $\beta=2$, the equations 26 are the criterions for the existence of the nth harmonic in a winding with $q_1=$integer. Thus, when $q_1=$integer,

$$\left.\begin{aligned}\frac{n'}{p}+1&=k \quad k=\text{integer excluding } 0\\ \left(\frac{n'}{p}\mp 1\right)\frac{1}{m_1}&=k_1 \quad k_1=\text{integer including } 0\end{aligned}\right\} \tag{27}$$

are the criterions for the existence of the n'th harmonic. Since n'/p is also an integer when $q_1=$integer, the first criterion says that the magnetomotive force of a single phase contains in general all odd as well as all even harmonics. The usually used 60-degree phase-belt winding does not contain even harmonics; for this winding k is limited to even integers.

The second criterion can be more conveniently used in the form

$$n'=(k_1 m_1+1)p \tag{28}$$

where k_1 is a positive as well as a negative integer including 0. For the normal 60-degree phase-belt winding, k_1 is again limited to positive and negative even integers including 0.

(b) The Rotor Harmonics

The n'th stator harmonic induces in the rotor phase designated by 0 the current

$$i_{2n'}=\sqrt{2}\,I_{2n'}\sin s_{n'}\omega t$$

$s_{n'}$ is the slip of the rotor relative to the n'th stator harmonic. To the current $i_{2n'}$ corresponds a rotor magnetomotive force, which contains different harmonics. We consider the m'th of these harmonics. Its magnetomotive force is

$$f_{2m'}=F_{2m'}\sin s_{n'}\omega t\cos m'\frac{x_2}{p\tau}\pi \tag{29}$$

We assume at first that the number of slots per pole per phase of the rotor is an integral number. Then the space angle between two adjacent phases is, as for the stator, $m'\frac{2\pi}{pm_2}$. The time angle between the electromotive forces of two adjacent rotor phases is determined by the n'th harmonic of the stator which produces the m' harmonic of the rotor, and since the space angle between two adjacent rotor phases is equal to $\frac{2\pi}{pm_2}$ this time angle is $n'\frac{2\pi}{pm_2}$. The time and space angle between the phase 0 and the cth phase are $n'\frac{2\pi}{pm_2}c$ and $m'\frac{2\pi}{pm_2}c$, and thus the resultant magnetomotive force

$$f_{2m'}=\frac{1}{2}F_{2m'}\left\{\left[\sin\left(s_{n'}\omega t-m'\frac{x_2}{p\tau}\pi\right)\times\sum_{c=0}^{c=m_2-1}\cos\,(m'-n')\frac{2\pi}{pm_2}c+\cos\left(s_{n'}\omega t-m'\frac{x_2}{p\tau}\pi\right)\sum_{c=0}^{c=m_2-1}\sin\,(m'-n')\frac{2\pi}{pm_2}c\right]+\left[\sin\left(s_{n'}\omega t+m'\frac{x_2}{p\tau}\pi\right)\sum_{c=0}^{c=m_2-1}\cos\,(m'+n')\times\frac{2\pi}{pm_2}c-\cos\left(s_{n'}\omega t+m'\frac{x_2}{p\tau}\pi\right)\times\sum_{c=0}^{c=m_2-1}\sin\,(m'+n')\frac{2\pi}{pm_2}c\right]\right\} \tag{30}$$

Since m' and n' are integers, the sums are equal to 0 except when

$$(m'-n')\frac{2\pi}{pm_2}=k_2 2\pi \quad k_2 \text{ integer including } 0$$

and

$$(m'+n')\frac{2\pi}{pm_2}=k_2 2\pi \quad k_2 \text{ integer including } 0$$

or except when

$$m'=k_2 pm_2+n' \tag{31}$$

For a given value of k_2 to any value of n' correspond two different values of m', that is, two traveling waves. Giving k_2 positive as well as negative values including 0, we can write

$$m'=k_2 pm_2+n' \quad k_2 \text{ positive or negative integer including } 0 \tag{32}$$

n' can be here, as before, positive or negative.

For the squirrel-cage rotor $m_2=\frac{Q_2}{p}$, and therefore

$$m'=k_2 Q_2+n' \tag{33}$$

While considering the wound rotor we have made the assumption $q_2=$integer. When $q_2=$fractional number it will be

$$m'=\frac{2}{\beta_2}k_2 pm_2+n' \tag{34}$$

This equation can be found by a similar consideration as for the stator.

Appendix 2. The Amplitudes of the Stator and Rotor Harmonics and the Speed of the Harmonics Relative to the Stator and to the Rotor

(a) The Stator Harmonics

For the n'th harmonic of the stator magnetomotive force

$$_1,t)=F_{n'}\sin\left(\omega t-n'\frac{x_1}{p\tau}\pi\right) \tag{35}$$

is valid, where

$$F_{n'}=\frac{\sqrt{2}}{\pi}m_1 N_1\frac{K_{d n'}K_{p n'}}{n'}I_1 \tag{36}$$

For the n'th harmonic of the field

$$b_{n'}(x_1,t)=B_{n'}\sin\left(\omega t-n'\frac{x_1}{p\tau}\pi\right) \tag{37}$$

where

$$B_{n'}=\frac{3.19}{g k_c k_s}\frac{\sqrt{2}}{\pi}m_1 N_1\frac{K_{d n'}K_{p n'}}{n'}I_1 \tag{38}$$

k_c is the Carter factor. The factor k_s takes into account the saturation. It is

$$k_s=\frac{AT_g+AT_{t1}+AT_{t2}}{AT_g} \tag{39}$$

For the higher values of n', k_s is to be set equal to 1, since the paths of these harmonics are through the tooth tops without penetrating further into the teeth and the core.

The velocity of the n'th harmonic of the field with regard to the stator will be found

by differentiation with respect to t of the equation

$$\omega t - n' \frac{x_1}{p\tau}\pi = \text{constant}$$

as

$$v_{1n'} = \frac{dx_1}{dt} = \frac{p}{n'}\frac{\tau}{\pi}\omega = \frac{P}{n'}v_p \qquad (40)$$

where

$$v_p = \frac{\tau}{\pi}\omega = 2\tau f_1 \qquad (41)$$

is the velocity of the main (synchronous) harmonic ($n' = p$).

In order to determine the electromotive force induced by the n'th stator harmonic in the rotor winding, it is necessary to know the velocity of this harmonic with regard to the rotor.

If s is the slip of the rotor relative to the main harmonic, the velocity of the rotor is

$$v_r = (1-s)v_p = (1-s)\frac{\tau}{\pi}\omega$$

and therefore

$$x_2 = x_1 - v_r t = x_1 - (1-s)\frac{\tau}{\pi}\omega t$$

or

$$x_1 = x_2 + (1-s)\frac{\tau}{\pi}\omega t \qquad (42)$$

Inserting this in equation 37 there will be found

$$b_{n'}(x_2, t) = B_{n'} \sin\left(s_{n'}\omega t - n'\frac{x_2}{p\tau}\pi\right) \qquad (43)$$

where

$$s_{n'} = 1 - \frac{n'}{p}(1-s) \qquad (44)$$

is the slip of the rotor with regard to the n'th stator harmonic. It is also

$$s_{n'} = \frac{f_{2n'}}{f_1} \qquad (45)$$

$f_{2n'}$ is the frequency of the electromotive force induced by the n'th stator harmonic in the rotor winding. It follows from equation 43 for the velocity of the n'th stator harmonic with regard to the rotor

$$v_{2n'} = \frac{dx_2}{dt} = s_{n'}\frac{p}{n'}v_p = s_{n'}v_{1n'} \qquad (46)$$

It follows further from equation 40

$$(\text{Rpm})_{n'} = \frac{P}{n'}n_s = \frac{60 f_1}{n'} \qquad (46a)$$

that is, the speed of a harmonic is inversely to its order. If there exists a fundamental ($n' = 1$), its speed relative to the stator will be equal to $60 f_1$, that is, 3,600 rpm for $f_1 = 60$ cycles per second. This is the highest speed that a stator harmonic can reach.

(b) The Rotor Harmonics

Corresponding to equation 37 we can write for the m'th harmonic of the rotor field

$$b_m(x_2, t) = B_{m'} \sin\left(s_{2n'}\omega t - m'\frac{\pi}{p\tau}x_2\right) \qquad (47)$$

This m'th rotor harmonic is produced by the n'th stator harmonic. The frequency of the rotor currents depends on the slip of the rotor relative to the n'th stator harmonic. For the amplitude $B_{m'}$ is valid (equation 4)

$$B_{m'} = \frac{3.19}{g k_c k_s}\frac{\sqrt{2}}{\pi} m_2 N_2 \frac{K_{dm'} K_{pm'}}{m'} I_{2n'} \qquad (48)$$

$I_{2n'}$ is the current induced in the rotor by the stator harmonic n'.

For the squirrel-cage rotor we have to insert in equation 48

$$m_2 = \frac{Q_2}{p}, \quad N_2 = 1/2, \text{ and } K_{dm'} = K_{pm'} = 1$$

Further, we have to multiply equation 48 by p, if we understand $I_{2n'}$ to be the current per slot. Thus the field amplitude $B_{m'}$ of the squirrel-cage rotor is

$$B_{m'} = \frac{3.19}{g k_c k_s}\frac{\sqrt{2}}{2\pi} Q_2 \frac{1}{m'} I_{2n'} \qquad (48a)$$

It follows from equation 33 (appendix 1) for the squirrel-cage rotor that its value of $B_{m'}$ is usually the larger the smaller is k_s. $k_s = \pm 1$ gives usually the largest value for $B_{m'}$.

From equations 47 and 44, it follows for the velocity of the m'th rotor harmonic with regard to the rotor

$$v_{2m'} = \frac{dx_2}{dt} = s_{n'}\frac{p}{m'}\frac{\tau}{\pi}\omega = \frac{p}{m'}\left[1 - \frac{n'}{p}\times (1-s)\right]v_p \qquad (49)$$

In order to study the noise problem it is necessary to know the velocity of the harmonics of the rotor fields with regard to the stator. Inserting in equation 47 the value of x_2 from equation 42

$$b_{m'}(x_1, t) = B_{m'} \sin\left[\left(1 + \frac{m'-n'}{p}(1-s)\right)\times \omega t - m'\frac{x'}{p\tau}\pi\right] \qquad (50)$$

The velocity of the m' rotor field harmonic with regard to the stator is thus

$$v_{1m'} = \frac{dx_1}{dt} = \frac{p}{m'}\left[1 + \frac{m'-n'}{p}(1-s)\right]v_p \qquad (51)$$

In the last two equations we have to substitute equations 32, 33, and 34 (appendix I)

$$\frac{m'-n'}{p} = k_3 m_2 \quad \text{for the wound rotor with } q_2 = \text{integer}$$

$$\frac{m'-n'}{p} = \frac{2}{\beta_2}k_3 m_2 \quad \text{for the wound rotor with } q_2 = \text{fractional number} \qquad (52)$$

$$\frac{m'-n'}{p} = k_3\frac{Q_2}{p} \quad \text{for the squirrel cage}$$

where k_3 is a positive or negative integer including 0.

We have seen that with $f_1 = 60$ cycles per second, the speed of the stator harmonics cannot exceed 3,600 rpm. The rotor harmonics are produced by currents of low as well as of high frequency. The speed that corresponds to the latter harmonics may be very high. It follows from equations 49 and 51

$$(\text{Rpm})_{2m'} = \frac{p}{m'}\left[1 - \frac{n'}{p}(1-s)\right]n_s \qquad (53)$$

and

$$(\text{Rpm})_{1m'} = \frac{p}{m'}\left[1 + \frac{m'-n'}{p}(1-s)\right]n_s \qquad (54)$$

We consider for example a squirrel-cage motor of 30 horsepower, four poles, 60 cycles, three-phase, with $Q_1 = 72$, $Q_2 = 58$ and examine the combination $n' = +62$, $k_3 = -1$, $m' = +4$. It follows from equations 53 and 54 with $s = 1.5$ per cent

$$(\text{Rpm})_{2m'} = \frac{1}{2}\left(1 - \frac{62}{2}\times 0.985\right)1{,}800 = 26{,}500$$

$$(\text{Rpm})_{1m'} = \frac{1}{2}\left(1 - \frac{58}{2}\times 0.985\right)1{,}800 = 24{,}800$$

The frequency of the rotor currents that correspond to the combination in consideration is (equation 44 or 45)

$$f_{2m'} = \left(1 - \frac{62}{2}\times 0.985\right)60 = 1{,}768 \text{ cycles per second}$$

Nomenclature

- b—Instantaneous value of the field intensity
- B—Amplitude of the field
- f—Instantaneous value of the magnetomotive force
- f—Frequency
- f_1—Line frequency
- F—Amplitude of the magnetomotive force
- h—Integer
- k—Number of force pole pairs
- k_d—Distribution factor
- k_p—Pitch factor
- k_c—Carter factor
- k_s—Saturation factor
- m_1—Number of stator phases
- m_2—Number of rotor phases
- m'—Order of the rotor harmonics
- m_{s1}'—Order of the slot harmonics of the rotor
- n—Speed (rpm)
- n'—Order of the stator harmonic
- n_{s1}'—Order of the slot harmonics of the stator
- N—Number of turns per phase
- p—Number of pole pairs
- q—Number of slots per pole per phase
- Q—Total number of slots
- s—Slip
- v—Velocity
- β—Number of poles per group, when q_2 = fractional number
- τ—Pole pitch
- $\omega = 2\pi f_1$

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Transient Recovery Voltages and Circuit-Breaker Performance

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EXPERIENCE with power circuit breakers has frequently shown that two breakers of identical design may give radically different performances, even though the operating voltages and short-circuit currents to which they are subjected are the same. Studies of the conditions surrounding these circuit breakers have traced the cause to the differences in the manner in which the recovery voltage has appeared across the contacts of the circuit breakers subsequent to the final interruption. This voltage which occurs between the final arc voltage and the 60-cycle recovery voltage is an equalizing phenomenon defined as the transient recovery voltage. To take it into account in breaker applications, studies have been made of the transient voltages which can occur on systems, and other studies have been made of the response of the circuit breakers to transient recovery voltages.

In the higher-voltage classes of circuit breakers, 34.5 kv and above, the voltage-recovery rates encountered in service are most severe when the circuit breaker is located adjacent to the power transformers. This is exactly the condition which is encountered in high-power laboratories, and so the recovery rates produced on the laboratory circuits for a given voltage and current closely approximate the maximum natural frequency and voltage-recovery rate which can be encountered in the service. In fact, service conditions will frequently involve the use of transmission lines supplying power to the circuit breaker. These lines may be supplying only a fraction of the total power which the breaker is called upon to interrupt, but the presence of the line on the bus greatly increases the capacitance of the circuit and reduces the rate at which the voltage appears across the breaker contacts. Consequently, when the voltages and currents can be duplicated on the laboratory high-voltage circuits, the transient recovery voltages obtained will probably be as severe or more severe than the transient recovery voltages encountered in service. A laboratory demonstration of the interrupting ability of a high-voltage breaker is, therefore, an excellent assurance of equally good service performance.

Studies of power-system circuits at generator voltage have revealed that the location of a reactor close to a circuit breaker produces a very high natural frequency in the transient recovery voltage. Some of these values have been found to be even higher than those encountered in normal high-power laboratory circuits. Very little was known about the performance of circuit breakers when subjected to these extremely high frequencies, and the need for additional data was apparent.

To eliminate this deficiency by studying transient recovery voltages having very high natural frequencies and to determine the effect of two-frequency transients, the tests described in this paper were made. These tests, made on four different types of circuit breakers, demonstrate the effects of various types of transient recovery voltages and show that the extremely high natural frequencies obtained with reactors close to breakers are not appreciably more severe on the circuit breakers than the natural frequencies normally obtained in the laboratory. They also reveal that tests made on the regular laboratory circuits may often be used to demonstrate the ability of the breaker to open under the most severe circuit conditions.

The Problem

Interrupting a circuit by a breaker consists of changing the current path through it from a good conductor to a good insulator. This is done preferably in as short a time as possible, with a minimum depreciation of breaker parts and as little external demonstration as possible. To accomplish this, the breaker separates the metallic current-carrying parts, thereby drawing an arc which temporarily completes the circuit. This current goes to zero periodically twice each cycle, and it is at one of these current zeros that the breaker completes the transition from a conductor to an insulator by deionizing the space between the contacts. An opportunity to do this occurs at each zero, but the arc will restrike if the voltage applied across the breaker exceeds the dielectric strength of the arc space. The dielectric strength of an ionized space has been defined by J. Slepian as the voltage required for sustaining or increasing the conductivity of the arc space, and it depends on the amount of ionization remaining and the rate at which the breaker is reducing it. The removal of the ionization requires time, and the breaker dielectric strength increases at a finite rate. This strength as defined above is finite at all times but increases toward the end of a half-cycle and just before current zero may attain high values. Unless at some time the applied voltage exceeds it, the dielectric strength will continue to increase after current zero, and the transition to an insulating state will be completed.

At the time of current zero in the

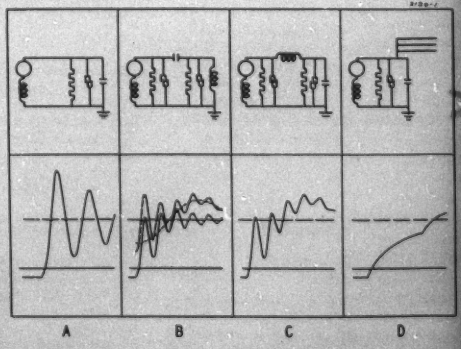

Figure 1. Typical simplified circuits and their corresponding transient recovery voltages

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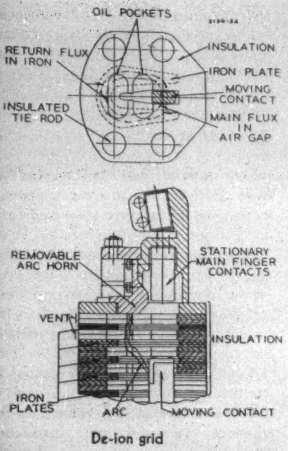
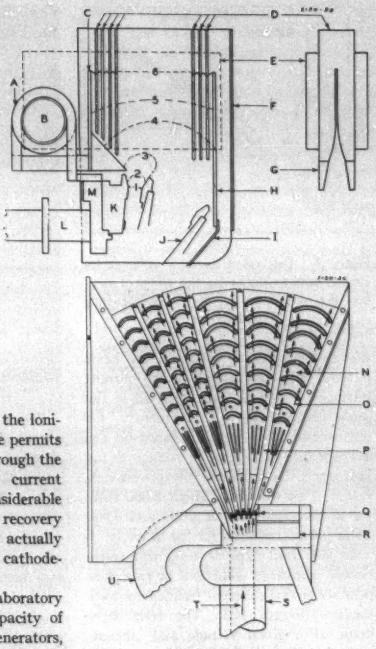


De-ion grid

Figure 2. Diagrammatic views of equipment used in these tests

Magnetic blowout air-breaker stack (right)

A—Magnet coil
B—Iron yoke
C—Panel-end horn
D—Insulation plates
E—Laminated iron shoes
F—Outline of arc chamber
G—Arc shield
H—Arcing horn
I—Shunt strap
J—Moving contact arm and arcing contact
K—Arcing and secondary contact platform
L—Micarta bushing
M—Upper stud



Compressed-air-breaker stack

N—Metal coolers
O—Exhaust gases
P—Insulation splitters
Q—Arc
R—Stationary contact
S—Tubular support
T—Air blast
U—Moving contact

breaker, the amount of ionization will sometimes be negligible, and at other times a sufficient amount may remain so that a current of a few amperes will flow through the arc space when the transient recovery voltage is applied across it.

The transient recovery voltage rises at a rate determined by the ability of the circuit to charge the capacitance adjacent to the breaker. The voltage does not increase at a constant rate nor always in the same general manner. The characteristics of the transient are determined primarily by the circuit constants. A simple circuit will have a transient recovery voltage which is essentially a sinusoidal wave as illustrated in Figure 1A. If the circuit breaker separates two parts of a circuit as shown in Figure 1B, each part will oscillate independently, and recovery voltage on the circuit breaker will be a two-frequency transient, the relative frequencies and amplitudes depending upon the inductances and capacitances of the circuit. A similar transient is produced by the more complicated circuit shown in Figure 1C. The addition of feeders to the bus, as shown in Figure 1D, may produce transients that are not sinusoidal.

These variations in the character of the transients are, of course, accompanied by variations in the speed with which they take place, as the inductances, capacitances, and number of lines are variable. The natural frequencies of the circuits used in these tests varied from 250 to 210,000 cycles per second.

The higher natural frequencies are caused by a low value of capacitance adjacent to the breaker, and only small currents flow into these capacitances during the transient. Consequently, if the ionization remaining in the arc space permits a comparable current to flow through the breaker in parallel with the current through the capacitance, a considerable modification of the transient recovery voltage is to be expected and actually takes place, as will be shown by cathode-ray oscillograms.

The circuits of a high-power laboratory for testing the interrupting capacity of breakers have one or more generators, current-limiting reactors, closing switches, backup breakers, and the circuit breaker on test. For convenience, the reactors are permanently installed as a part of the laboratory equipment and are provided with suitable switching arrangements for varying the effective value of the reactance in the lines over a relatively wide range. Consequently, the capacitance of the bus and switches between the reactor and the circuit breaker may be greater than it would be in a power station having the current-limiting reactors located within a few feet of the circuit breaker. To determine how much effect this additional capacitance might have and to extend the range of tests up to as high values as could be obtained, reactors were placed in the test cells with the breakers and were connected to them by short leads.

Four types of breakers were studied. The first was an oil circuit breaker using plain-break-type contacts with no means of controlling or directing the gases generated in the oil. The second was also an oil breaker but was equipped with modern arc-rupturing devices ("De-ion grids"), Figure 2. It belonged to the class of breakers using self-generated gas blasts. The third was an air circuit breaker which produced a magnetic blast to drive the arc into a confining slot. The fourth type was the compressed-air circuit breaker which subjected the arc to a transverse blast of compressed air and forced it against arc splitters.

Because of the various transients which may be encountered, three different types of tests were used.

In one type of test, the single-frequency transients, illustrated in Figure 1A, were used with the voltage and current constant and the capacitance varied. These tests demonstrated the effect of varying the natural frequency of the transient over a very wide range.

Another type of test covered a wide range of currents at a given voltage. Two series of tests were made, differing only in the natural frequency of the transient recovery voltage. Due to the inductance varying with current and the limitations within which the capacitances of the laboratory could be controlled, it

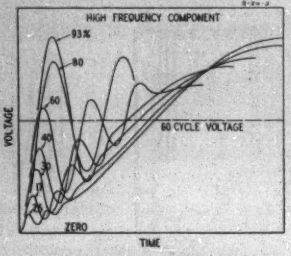


Figure 3. Calculated transient voltages for circuits used to determine the effect of varying the amplitude of the high-frequency component

was not possible to maintain the same natural frequency for all of the current settings or even to keep them all of the same general type. Consequently, for comparison, they were all based on the average rate of increase in voltage to the first peak, the transient voltage-recovery rate. This value was about 2,000 volts per microsecond for one group and 3,000 volts per microsecond for the other.

In the third type of test, voltage-recovery transients composed of two components having different frequencies were studied (Figure 1C). The tests were made at a given voltage and current, and, by varying the distribution of the impedance in the circuit, the amplitude of the high frequency component was varied from 7.5 to 93 per cent of the total amplitude of the transient (Figure 3). This was done to determine how high the first peak of voltage had to be before it exerted an influence on the performance of the circuit breaker. If the amplitude of the higher frequency component is relatively small, the voltages reached during the part of the transient controlled by it may be so low that they exert little or no influence on the breaker performance. However, if the amplitude of the higher-frequency component is relatively high, the transient approximates a single-frequency transient and naturally produces practically the same effect.

All tests were made on single-phase 60-cycle circuits. The 7,620-volt circuits had one side of the breaker grounded. The 13,200-volt circuits had the neutral of the generator grounded through a resistor. Records were made on a magnetic oscillograph and on a cathode-ray oscillograph having a rotating film drum. To expedite the testing, records of two similar tests frequently were made on one cathode-ray-oscillograph film using two different time scales.

Plain-Break Oil Circuit Breaker

The tests on the oil circuit breaker not equipped with arc-extinguishing devices demonstrated its performance over a wide range of circuit voltage-recovery rates. The breaker used had a tank diameter of 30 inches, a contact stroke of $11\frac{1}{8}$ inches and an average contact opening speed of 8.2 feet per second. The two breaks were each ten inches long. All tests were single-phase with one side grounded at the breaker. The tests were close to the voltage-interrupting ability but were well below the current-interrupting ability of the breaker.

A series of tests was made to determine the effect of varying the natural frequency of the circuit. This was done on a 7,620-volt 5,200-ampere circuit but at a potential of about 3,810 volts and a current of 2,600 amperes. A wide range of natural frequencies was obtained. The highest frequency, 208,000 cycles per second, resulted from placing a 1.2-ohm reactor in the test cell immediately adjacent to the circuit breaker. The lower values, down to 380 cycles per second, were obtained by various laboratory circuit connections and by adding capacitance to the normal laboratory circuit. The arcing time was a function of the natural frequency as shown by Figure 4.

The cathode-ray oscillograms, Figure 5, show that at the higher frequencies the oscillations of the transients were completely damped, and the damping became relatively less at lower frequencies so that the maximum voltage which was reached during the extinction transients varied as shown in Figure 4. The voltage reached by the transient a half-cycle before interruption was also measured and plotted in Figure 4. At the higher frequencies, these voltages were well below the voltages reached on the final transient. However, as the frequency was reduced, and the energy of the transient was increased, the voltage on the transients increased and approached double the normal crest of the sixty-cycle wave. As this approximates the normal maximum voltage of a recovery transient, further reduction in frequency permitted the arc to extinguish on this transient which then became the final transient. The group of crosses representing maximum voltages on final transient recovery voltages for 500 to 600 cycles per second can be considered an indication of the end of this curve.

An interesting discontinuity exists in the arcing time curve at about this frequency. The breaker seemed to make a good effort to extinguish the arc within the first cycle and, if it failed to do so, would be unable to accomplish it until about the end of the third cycle of arcing. Below 400 cycles per second the breaker interrupted with about one-half cycle of arcing.

At six of the steps the maximum voltage which could be consistently interrupted was determined and was found to be about 3,810 volts 2,600 amperes. At higher voltages occasional failures occurred, and this limit appeared to be independent of the natural frequency of the circuit.

Two other series of tests were made to determine the effect of the amplitude of the higher-frequency component of two-frequency transients. They were planned and made prior to the series described above and before it was known that this breaker had a constant arcing time over such a wide range of natural frequencies. The lower frequencies chosen were as low as could be easily obtained but varied from 2,700 to 8,000 cycles per second on the low-current series and from 7,000 to 17,000 cycles per second on the higher-current series. These series gave data

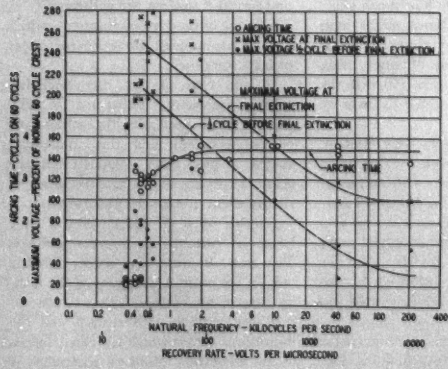

ARCING TIME
MAX VOLTAGE AT FINAL EXTINCTION
MAX VOLTAGE ½ CYCLE BEFORE FINAL EXTINCTION
MAXIMUM VOLTAGE AT FINAL EXTINCTION
½ CYCLE BEFORE FINAL EXTINCTION
ARCING TIME
ARCING TIME – CYCLES ON 60 CYCLES
MAXIMUM VOLTAGE – PERCENT OF NORMAL 60 CYCLE CREST
NATURAL FREQUENCY – KILOCYCLES PER SECOND
RECOVERY RATE – VOLTS PER MICROSECOND

Figure 4. Plain-break circuit breaker, 3,800 volts, 2,600 amperes

Effect of natural frequency of transient recovery voltage

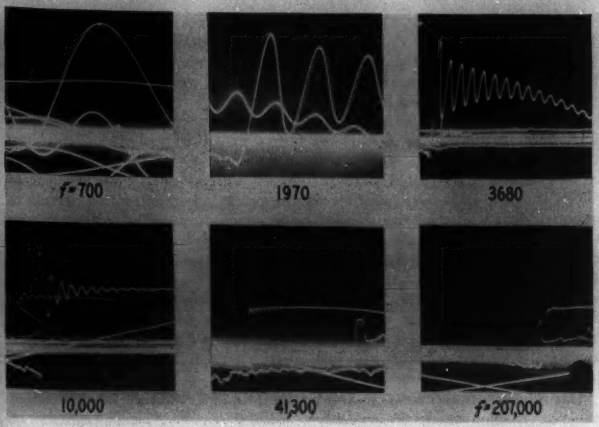


Figure 5. Plain-break circuit breaker, 3,800 volts, 2,600 amperes

Cathode-ray oscillograms showing effect of conductivity in the arc space on the transient recovery voltage

which indicated that at both currents the arcing time was substantially independent of the amplitude of the higher-frequency component, and this result was difficult to explain until the effect of varying the single-frequency transients over much wider ranges was disclosed by the later test. Consequently, the data on these tests are of interest in supplementing the previous data and in showing the effect of the conductivity of the arc space on the damping of the double-frequency transients.

In one series of tests, made with a current of 1,400 amperes at 3,180 volts, the amplitude of high-frequency component was varied from 7.5 to 93 per cent of the total amplitude in about ten per cent steps. The transients calculated during the planning of the test are shown in Figure 3, and the transients actually obtained are shown in Figure 6. The actual transients were modified considerably by the current being passed through the arc space of the circuit breaker.

The transients having calculated high-frequency components of 80 and 90 per cent were so heavily damped by the current through the arc space that they appeared aperiodic. Data from these tests are plotted in Figure 7 as a function of the amplitude of the calculated high-frequency component. The arcing time remained substantially constant. The maximum peak voltage decreased almost linearly, indicating that the higher-frequency component had negligible amplitude at the time of the maximum crest. The first peak increased almost linearly with the amplitude but at a rate only about half as great as would have been reached without conductivity in the arc space.

A similar series of tests were made at higher current, 6,000 amperes at 3,050 volts with high-frequency components having from 7 to 75 per cent of the total amplitude. For these values also the arcing time was independent of the amplitude of the high-frequency component, Figure 8. The conductivity was sufficient in all cases to damp completely the high-frequency component, and in some cases, the low-frequency component also. The low-frequency components increased in frequency as the amplitude decreased, but the range was only from 7,000 to 17,000 cycles per second. The constant arcing time and the damping of the transients indicates that the breaker easily dissipated all of the energy of the high-frequency component and that arcing times were the same for either the high or the low frequency.

The maximum voltage-interrupting ability was found at each setting by making tests at increasing voltages until failure occurred. The limit was found to be approximately the same for all of these circuits. The breaker failed on about half of the tests at 3,430 volts 6,750 amperes.

The tests on the plain-break oil circuit breaker operating near its maximum voltage-interrupting ability indicates that conductivity of the arc space following the normal current zero plays a big part in modifying the transients. The very slow high-energy transients are not appreciably affected as the energy loss is relatively low. As the frequency increases, and the energy decreases, the losses through the breaker result in increasing damping of the transients. At high natural frequencies, the admittance of the parallel capacitance path is so much smaller than the conductivity of the arc space that the capacitance current becomes negligible. Consequently, although reducing the capacitance further can greatly increase the natural frequency of the circuit and the calculated voltage-recovery rate, the actual transients obtained on test or in service will not be changed. When the conductivity damps out the higher-frequency components, the lower-frequency greater-energy components become more important. No increase in arcing time occurs with increase in natural frequency above the value where conductivity modifies the transients.

Only at natural frequencies below 2,000 cycles per second, corresponding to less than 45 volts per microsecond, did the arcing time decrease with decrease in frequency. Above 2,000 cycles per second, the arcing time was independent of the natural frequency or of the combination of components in double-frequency transients.

"De-ion Grid" Oil Circuit Breakers

The breaker used for this part of the test had a tank diameter of 30 inches, a stroke of 11⅛ inches, a contact separation of 10 inches and an average opening speed of about 8.2 feet per second. It was equipped with a heavy-duty type of "De-ion grid" of the type shown in Figure 2. The breaker was tested at normal operating voltages but well below its interrupting ability.

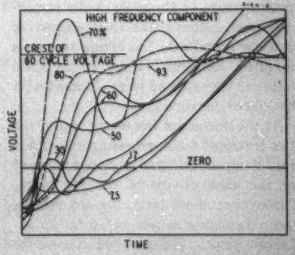


Figure 6. Plain-break circuit breaker, 3,800 volts, 2,600 amperes

Tracings of cathode-ray oscillograms for comparison with calculated transient voltages of Figure 3

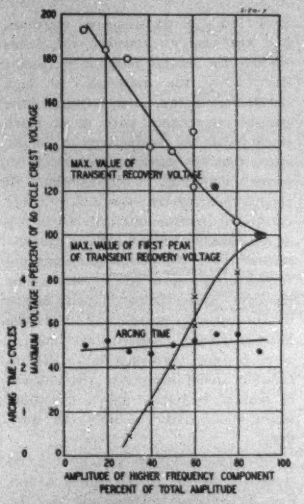

MAX. VALUE OF TRANSIENT RECOVERY VOLTAGE
MAX. VALUE OF FIRST PEAK OF TRANSIENT RECOVERY VOLTAGE
ARCING TIME
ARCING TIME - CYCLES
MAXIMUM VOLTAGE - PERCENT OF 60 CYCLE CREST VOLTAGE
AMPLITUDE OF HIGHER FREQUENCY COMPONENT
PERCENT OF TOTAL AMPLITUDE

Figure 7. Plain-break circuit breaker, 3,800 volts, 2,600 amperes

Effect of the amplitude of the higher-frequency component

The tests made on this breaker were similar to those made on the plain-break circuit breaker. In many cases the circuits were the same, but the voltages and currents were higher.

One series of tests was made to determine the effect of varying the frequency of a single-frequency transient. This test was made at 7,620 volts 5,350 amperes. Frequencies from 375 cycles per second to 209,000 cycles per second were used.

The arcing time obtained on these tests varied with the natural frequency and voltage-recovery rate as shown in Figure 9. At the lower values the arcing times were less with a gradual rise up to a recovery rate of about 200 volts per microsecond. Above this voltage-recovery rate, no increase in the arcing time was obtained, although values up to 8,500 volts per microsecond were obtained with 209,000 cycles per second.

At the maximum frequency two of the four transient recovery voltages recorded were damped, and two were not damped by the conductivity of the arc space. Throughout these tests, the arc voltage had a tendency to rise and form an extinction peak. This resulted in some increase in the amplitude of the transient. The extinction peak indicates rapid deionization of the arc space and a high effective resistance at current zero. Consequently, damping of the transient was observed only at the highest natural frequency where the total energy of the oscillation was very small.

The preceding tests were supplemented by another series which showed that at 13,200 volts 8,000 amperes, the arcing time was constant for natural frequencies from 3,900 cycles per second up to 200,000 cycles per second. The highest natural frequency was practically completely damped by the energy discharged into the arc spaces, and the transient showed only the 32,000-cycle per second component having an amplitude about 15 per cent of the total. At the next step which had frequencies of 26,000 cycles and 42,000 cycles per second, the highest-frequency component was not appreciably damped, and the extinction peaks were definitely increased.

This breaker was also tested to determine its reaction to double-frequency transients. When the higher-frequency component is either very large or very small, the performance can be expected to be the same as the performance obtained with single-frequency transients corresponding to the predominant frequency. Accordingly, a series of tests was made at 7,620 volts 5,200 amperes with transients having components of two frequencies, one normally causing a shorter arcing time than the other. As the amplitude of the higher-frequency component increased, the arcing time increased as shown in Figure 10. The change in arcing time is gradual, and even small high-frequency components exert a noticeable influence.

These same relations were demonstrated at 15,000 amperes 7,620 volts, as shown on the same curve. The lower frequency varied from 594 cycles per second at the lower amplitude of the high-frequency component to 1,280 cycles per second at the higher amplitudes. These frequencies may be a little higher than those producing minimum arcing and may explain why the arcing time does not increase for high-frequency components greater than about 65 per cent of the total amplitude.

An attempt to get a similar curve at 7,620 volts 2,800 amperes failed, because at the lowest frequency available, 250 cycles per second, the arcing time was as long as at the higher frequencies. The first peak of the transient recovery voltage increased approximately linearly with the increase in amplitude of the higher-frequency component and indicated a negligible damping of the high-frequency component by the conductivity of the arc space. The maximum voltage reached during the transient was highest when one of the two components predominated and was lower when the two components approached each other in magnitude. The arcing time was practically independent of both the first peak and the maximum voltage of the transient.

The tests on this breaker demonstrated that the effect of single-frequency transients varied with the current. At 2,800 amperes no appreciable increase in arcing time resulted from increasing the natural frequency of the circuit above 250 cycles per second. At 5,200 amperes the corresponding point was 3,000 to 4,000 cycles, and at 15,000 amperes it was about 10,000 cycles.

Double-frequency transients demonstrated that the breaker performance varied gradually with the amplitudes of the two components. The limits were the two end conditions which occurred when either the higher-frequency or lower-frequency component was negligible.

Magnetic Blowout Air Circuit Breaker

During the development of a magnetic blowout air circuit breaker, tests were made in the high-power laboratory on single-phase circuits giving about 15,000 amperes at four kilovolts to determine the effect of recovery voltages on the arcing time and voltage-interrupting ability. These values were near the maximum interrupting capacity of the breaker. By

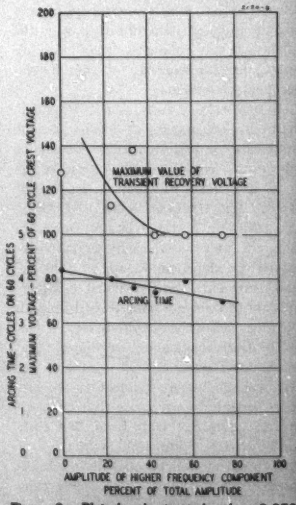

MAXIMUM VALUE OF TRANSIENT RECOVERY VOLTAGE
ARCING TIME
ARCING TIME - CYCLES ON 60 CYCLES
MAXIMUM VOLTAGE - PERCENT OF 60 CYCLE CREST VOLTAGE
AMPLITUDE OF HIGHER FREQUENCY COMPONENT
PERCENT OF TOTAL AMPLITUDE

Figure 8. Plain-break circuit breaker, 3,050 volts, 6,000 amperes

Effect of the amplitude of the higher-frequency component

varying the capacitance of the circuit, natural frequencies from 3,880 cycles per second to 12,000 cycles per second were obtained. For still lower transient recovery voltages a resistor was connected across the breaker to simulate a parallel resistive load. Some of the transient recovery voltages obtained are reproduced in Figure 12.

The arcing time was less than one cycle and independent of the transient recovery voltage. This indicated that the arc was interrupted at the first current zero after it had reached a suitable location in the arc chute. The arc voltage prior to interruption was relatively high and smooth. The lack of an extinction peak indicated that there would be some conductivity in the arc space subsequent to the current zero, and this is further indicated by the subsequent damping of the recovery transients. The damping is very noticeable on the circuits having high frequencies at which the current through the arc space is comparable to the current into the capacitance. At the lower frequencies the damping is less pronounced, as the current into the capacitance is large with respect to the current through the arc space.

How large this current into the parallel capacitance can become is illustrated in a striking manner in Figure 13. This is a section of an oscillogram made on one of the tests at 4.4 kv, a little above the interrupting ability of the breaker, and on a circuit having a large parallel capacitance obtained by connecting to it three large power transformers. The natural frequency of the transient recovery voltage was 4,000 cycles per second. Due to the high test voltage, the arc continued to restrike, and traces of the natural frequency of the transient recovery voltage appear in the arc voltage. The transient at the time of restriking excited the resonant circuit and produced a sinusoidal current in it which modified the current through the circuit breaker sufficiently to produce a sinusoidal ripple on the arc voltage.

With the transient recovery voltages of an oscillatory character, the breaker could interrupt about 4 kv regardless of frequency of the oscillation. By placing a resistor across the breaker to simulate a parallel resistive load, the breaker was able to interrupt 4.95 kv. Possibly the increase in the voltage was due to elimination of the tendency of the transient recovery voltage to reach crest voltages in excess of the normal crest of the 60-cycle recovery voltage.

This type of breaker, having a relatively high arc voltage, appears to be sensitive to the crest value which may be reached by the transient recovery voltage, but the arcing time remained constant from 3,880 to 12,000 cycles per second.

Compressed-Air Circuit Breakers

The compressed-air circuit breaker was the fourth type to be included in this investigation. One series of tests, made on a 15-kv 1,500,000-kva breaker with currents up to 36,000 amperes, showed that for circuit voltage-recovery rates of 1,500 to 2,250 volts per microsecond, the arcing time was substantially constant and lasted only to the first current zero after the contacts had been separating for one-tenth cycle. This resulted from the ability of the breaker to interrupt currents in this range at the first current zero, after contact separation adequate to hold this voltage was reached. Another series of tests over the same range, but with higher recovery rates varying from 2,600 to 3,800 volts per microsecond, showed that the minimum contact separation at which arc extinction could be accomplished varied with current. It corresponded to an arcing time of 0.35 cycle at 6,000 amperes (the same as for the lower recovery rate), and to an arcing time of about one cycle at 36,000 amperes, as shown by Figure 14.

This increase in arcing time with current was not due to a corresponding increase in voltage-recovery rate. The increased arcing time was apparently associated with the increased difficulty of interrupting the heavier currents which have greater quantities of ionized gases and which approach current zero at higher rates.

This is an important relation, since it indicates the nature of the mechanism by which arc extinction is brought about. It indicates that the arc column is being deionized, and that this process requires more time as the diameter of the arc (and its current) increases. If the arc extinction were brought about by a breaking of the arc column and the separation of the two ionized sections of the arc, higher recovery-voltage rate, rather than higher current would require additional arcing time for the introduction of additional arc splitters.

These tests also show the sensitivity of the compressed-air circuit breaker to relatively low high-frequency components in the transient recovery voltage. At the maximum current setting and the lower recovery rate, 2,200 volts per microsecond, the transient was composed of a single component having a frequency of 28,500 cycles per second. For the higher recovery rate, about 2,600 volts per microsecond, the transient had two compo-

Figure 9. "De-ion grid" oil circuit breaker, 7,620 volts, 5,350 amperes

Effect of natural frequency of transient recovery voltage

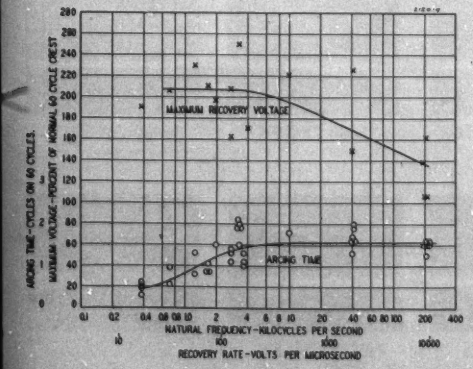
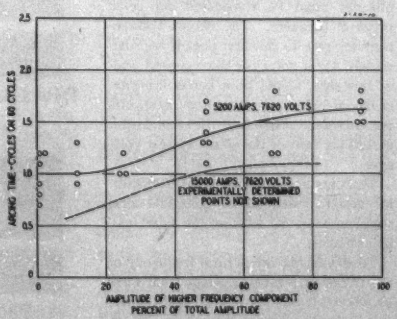

MAXIMUM RECOVERY VOLTAGE
ARCING TIME
ARCING TIME-CYCLES ON 60 CYCLES
MAXIMUM VOLTAGE-PERCENT OF NORMAL 60 CYCLE CREST
NATURAL FREQUENCY-KILOCYCLES PER SECOND
RECOVERY RATE-VOLTS PER MICROSECOND

Figure 10. "De-ion grid" oil circuit breaker

Effect of the high-frequency component is roughly proportional to amplitude



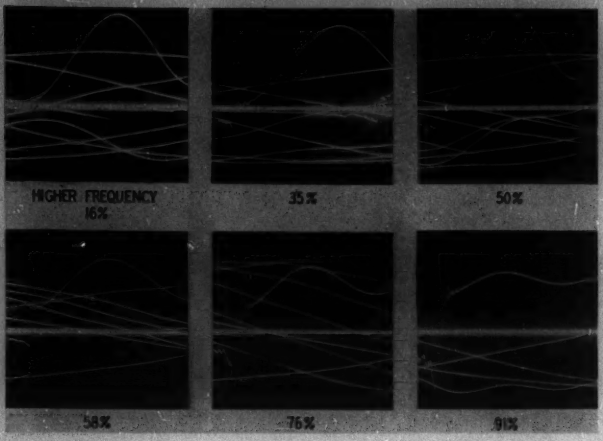


Figure 11. "De-ion grid" oil circuit breaker, 7,620 volts, 15,000 amperes

Cathode-ray oscillograms showing variation in high-frequency component

nents with frequencies of 33,600 and about 190,000 cycles per second. The amplitude of the 190,000-cycle component was only about 25 per cent of the total amplitude of the transient, but as shown by Figure 14, it caused at least a half-cycle increase in arcing time, and the last breakdown occurred at approximately the crest of this first peak of voltage, about 45 per cent of the crest of the 60-cycle recovery voltage.

The circuit transient recovery voltage on this setting, which would be based on zero arc voltage, would have a first crest of voltage about 57 per cent of the 60-cycle crest. This crest is below the 80 per cent which has been used as an arbitrary minimum voltage to be used in calculating circuit transient recovery voltage rates and emphasizes that lower amplitudes must be considered for some types of breakers. The circuit voltage-recovery rate to this first peak is approximately 4,600 volts per microsecond and, in this case, would be a better criterion of the circuit severity than the 2,600 volts per microsecond based on the second peak at 120 per cent of the 60-cycle crest voltage.

Tests made on another breaker of similar design, rated 15 kv 2,500,000 kva, supplemented the tests on the 1,500,000-kva breaker.

Tests varying the natural frequency of the transient recovery voltage from 3,900 to 200,000 cycles per second, and the circuit voltage-recovery rate from 300 to 13,600 volts per microsecond were made at 8,000 amperes 13,200 volts. The arcing time was practically constant over the entire range, varying in minimum and maximum value by only one or two tenths of a cycle.

The series of recovery voltage transients obtained on these tests and shown in Figure 15 is particularly significant and interesting. They show that at the lower frequencies, the transient is almost unaffected by the conductivity of the arc space. With smaller parallel capacitances, the charging current is less, and therefore the current through the breaker is relatively greater. The breaker current at moderate frequencies resulted in partial damping of the transient and finally at high frequencies became the controlling factor when the capacitance current became negligible with respect to it.

Other tests were carried up to 100,000 amperes, and the oscillograms indicated that the larger the current interrupted, the lower the effective resistance of the arc space at the final current zero. The approximate relations are shown on Figure 16. These resistances permitted sufficient current to flow subsequent to the normal current zero to partially damp the recovery transients at the higher currents.

Discussion

These studies of four types of circuit breakers indicate certain points of similarity in their performance, even though the manner in which arc extinction is produced within the interrupter differs considerably in detail between types. All of these types of breakers modify the transient recovery voltages. The means by which this is accomplished is the same, but the range in which the modification begins to appear, and the range in which it overcomes completely the oscillating tendency of the circuit vary with the types of breakers and not necessarily in relation to their rated voltages and rated interrupting currents.

All of the circuit breakers were tested over a sufficiently wide range to include both modified and unmodified transient recovery voltages. The modification was produced by the breaker when it passed a small current through the arc space subsequent to the final normal current zero. This was evidenced by the transient recovery voltage departing from the values

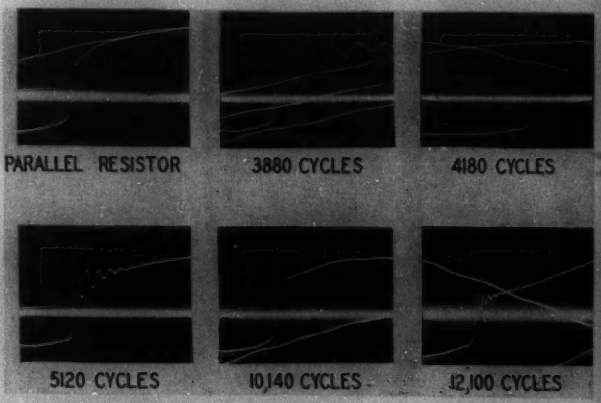


Figure 12. Magnetic blowout air circuit breaker, 4 kv, 15,000 amperes

Effect of natural frequency of transient recovery voltage

Figure 13. Magnetic blowout air circuit breaker, 4.4 kv, 16,500 amperes

Large power transformers connected to the same generator produced these oscillations in the arc voltage during an unsuccessful attempt to interrupt the circuit

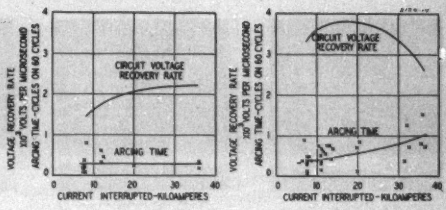


Figure 14. Compressed-air circuit breaker

Arcing time as a function of current interrupted for two series of tests made with different transient recovery voltages

which could be calculated for the circuit if all conductivity of the arc space was neglected. Also, the transient varied from test to test on the same circuit depending upon the conditions existing within the circuit breaker. The arc conductivity and rate of deionization are indicated roughly by the arc voltage prior to current zero.

The conductivity of the arc space at the time of current zero varies with the current being interrupted. This conductivity is a function of the ionization during the preceding half-cycle and the rate at which the space is being deionized. The ionization is produced by the current which will approach zero at a rate approximately a direct function of the rms current being interrupted. The residual ionization will depend on how rapidly these ions are removed.

In circuit breakers which use the energy of the arc to produce the deionizing effect, the rate of deionization might vary directly with the rms current, with the result that the right amount of deionizing activity would be present for each current. The larger the rms current being interrupted, the greater the rate at which the current approaches zero and the stronger the deionizing effect. The production and effectiveness of the deionizing action is probably never directly proportional to the current. Published data have frequently shown that breakers with self-generated deionizing action have shorter arcing times at high currents than at low currents. These shorter arcing times indicate that the deionizing activity produced by the arc is relatively stronger at the high currents.

Other breakers may have a deionizing activity produced by some source which is entirely independent of the current to be interrupted. For example, a compressed-air breaker delivers a deionizing blast of air, determined by the design of the circuit breaker and independent of the current being interrupted.

When very low values of current are interrupted, the deionizing activity may keep up with the current, and the conductivity at the current zero may be practically zero. Oscillograms made on various types of breakers show that even a short time before the normal zero in these low-current circuits, the arc may become unstable and extinguish suddenly, the current to the arc space transferring at this time to the path through the parallel capacitance of the circuit and resulting in a rise in the voltage across the breaker at the beginning of the transient recovery voltage. The oscillograms also show that this phenomenon, which mathematically can reach enormous voltages, is still under the control of the breaker, because, as the voltage rises, it cannot exceed the dielectric strength of the space between the contacts without the arc restriking. This dielectric strength, determined by ionization and contact separation, limits the voltages if an attempt is made to interrupt the current so early that the voltage rise is rapid and high. Oscillograms of a large number of tests on several oil and air breakers have indicated that the maximum voltage obtained in this manner probably is not over three times the normal crest of the line to ground voltage.

In other cases, the conductivity of the arc space may become zero as a current zero is reached, and the transient recovery voltage takes place in a manner which can be explained entirely on the basis of the inductance, capacitance, and losses of the power circuit. This type of phenomenon which is generally assumed in calculations may occur only at low currents, or it may extend even up to the rated interrupting current. In general, test data show that as the current is increased, the tendency for some of the ionization to remain at the time of current zero increases. From oscillograms made on the compressed-air circuit breaker, a curve was plotted to show qualitatively the relation between the equivalent resistance of the arc space at the time of current zero and the current which was being interrupted. Other types of breakers, including those having self-generated arc-extinguishing actions, have similar curves.

The residual ionization, lasting for an appreciable time interval after the normal current zero, acts as a variable resistor connected across the terminals of the circuit breaker. This residual ionization or conducting path between the breaker contacts permits a current to flow through the breaker during the time of the transient recovery voltage. This current is a function of the equivalent resistance of the arc space and the voltage impressed across it. It probably has only a very low current density in this space, and the deionizing activity can remove more ions than it produces. Calculations based on the voltage records and knowledge of the circuit characteristics have indicated that currents up to approximately 30 amperes have been carried through the arc space of breakers without the actual formation of an arc. The maximum value of current which can flow during this period without producing an arc probably depends upon the previous current and upon the design of the interrupter.

The actual value of current which flows through the arc space during the transient is, of course, very small with respect to the short-circuit current. In fact, it is too small to be indicated on a normal magnetic oscillogram of the interruption of a short circuit. It flows for only a part of the time consumed by the transient recovery voltage and is detected by its influence on it.

The significance of this small current lies in its magnitude with respect to the charging current which flows into the capacitance in parallel with the breaker. This capacitance can vary within wide limits. Its minimum value corresponds to the capacitance to ground of one terminal of a circuit breaker, a few feet of conductor, and one end of a reactor. Consequently, this current too can be very small. With about 200 micro-

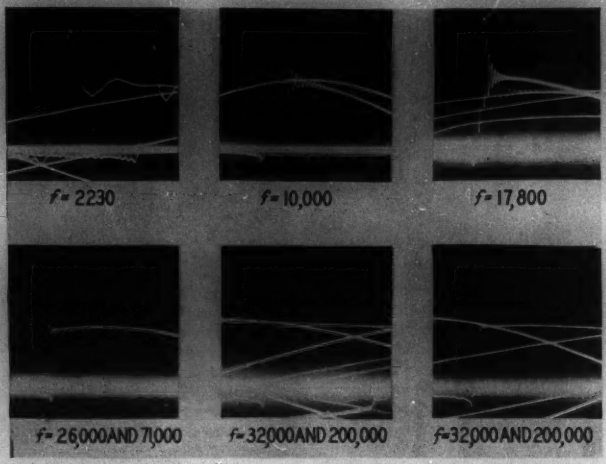


Figure 15. Compressed-air circuit breaker, 13,200 volts, 8,000 amperes

Cathode-ray oscillograms showing the effect of the natural frequency of the transient recovery voltage

microfarads, 200,000 cycles per second, and 7,600 volts rms to ground, it would be about two amperes. When the current through the breaker becomes comparable with the capacitance current, either by the increase of the one or the decrease of the other, it begins to exert a damping influence on the transient recovery voltage and, when large enough, critically damps the transient. For still larger currents through the arc path, the small current flowing into the capacitance becomes negligible, and the transient recovery voltage rises as though it were the voltage appearing across the resistance in a simple circuit containing resistance and inductance in series. As these values of resistance current and capacitive current are relative, the same results can be obtained by reducing the capacitance and thereby the capacitive current until such a point is reached that the current through the arc space is greater than the current through the parallel capacitance. These relations were demonstrated by these tests.

The testing of circuit breakers carried on in high-power laboratories at generator voltage can approximate closely the conditions under which the circuit breaker is to be used in service. The effects, if any, of differences in frequencies of the transients can sometimes be evaluated by a study of the test data to give a definite indication of the manner in which the breaker will perform in service.

The tests on the plain-break circuit showed that at very low values of natural frequency the recovery voltages were undamped. At higher natural frequencies damping of the transient recovery voltage appeared, and after a point of critical damping had been reached, further increase in the natural frequency of the transient recovery voltage resulted in no appreciable change in the actual voltage appearing across the circuit-breaker contacts. This was produced by the effect of the currents through the circuit breaker subsequent to the current zero. This current passing through the breaker was so large with respect to the current flowing into the parallel capacitance of the circuit that it controlled the transient recovery voltage, making it approach an exponential curve. After the point of critical damping was reached, further reduction in the capacitance across the terminals of the circuit breaker did not result in further increase in the severity of the duty on the circuit breaker. This was carried over a wide range above the critical damping without producing any appreciable change in these transients (Figure 5).

A similar set of cathode-ray oscillograms was obtained on the compressed-air circuit breaker, operating at a different current and voltage (Figure 15).

These data demonstrate that if a circuit breaker can successfully interrupt a given voltage and current and critically damp the transient recovery voltage, it can interrupt any other circuit having the same voltage and current and less parallel capacitance without any increase in the severity of the duty on the breaker.

Conclusions

These tests supplement each other to give a picture of the phenomena of arc interruption by high-power circuit breakers. They show that the interruptions brought about by air or oil breakers are similar in characteristics. In circuits having a low natural frequency, the recovery of the dielectric strength of the arc space proceeds with negligible influence exerted upon it by the slowly rising transient recovery voltage. The maximum value of the dielectric strength depends upon the distance between the contacts and the condition of the fluid or fluids filling the space. Above certain values of current and natural frequency, depending on the design of the breaker, the transient recovery voltage is impressed on the arc space while considerable ionization still remains. Consequently, a small current flows through this space, thereby hindering further deionization and modifying the transient recovery voltage. For very high natural frequencies this current may exceed the parallel current through the capacitance across the breaker and may control the transient recovery voltage. If the discharge current becomes too high, it develops into an arc which conducts current till the next normal current zero. The values of voltage, current, and natural frequency at which these phenomena occur vary with the designs of the breakers and not in proportion to their rated interrupting capacities.

The difficulty of circuit interruption

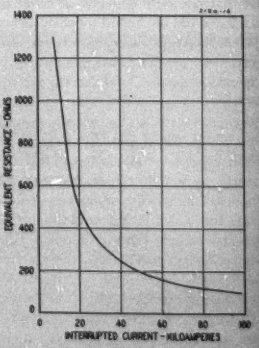


Figure 16. Compressed-air circuit breaker

Approximate resistance of the arc space at the time of the final current zero as a function of the current interrupted

does not increase indefinitely with increase in the natural frequency of the circuit. The speed with which the circuit tends to apply the transient recovery voltage to the circuit breaker varies directly with the natural frequency. However, if the current passed through the arc space is greater than the current through the capacitance across the breaker, further decrease in the capacitance does not materially increase the actual rate at which the voltage appears across the contacts and, consequently, does not make the circuit more difficult to interrupt.

The maximum arcing times on these tests were reached with transient recovery voltages having natural frequencies which were not heavily damped by the conductivity.

The tests indicate that the effect of the high-frequency component of a two-frequency transient voltage varies almost in proportion to the amplitude of the component. The effect is negligible when both frequencies tend to produce the same arcing time.

The transient recovery voltages obtained on high-voltage circuits energized through transformers can be equalled in high-power laboratories within the range of voltages and currents available. The laboratory circuits closely approximate the severe service conditions as the leads between the transformers and breakers are short. The lead capacitance is small with respect to the transformer capacitance, and, consequently, small variations in it are not significant.

At generator voltages, the reactors in the laboratory circuits have natural frequencies which are sufficiently high to produce the maximum arcing times in circuit breakers.

The plain-break oil circuit breaker at 3,800 volts 2,600 amperes did not increase in arcing time for natural frequencies above about 2,000 cycles per second. Similar points were found for the "De-ion grid" oil breaker, 250 cycles per second for 2,800 amperes, 7,620 volts, 3,000 to 4,000 cycles per second for 5,200 amperes, and 10,000 cycles per second for 15,000 amperes. The compressed-air breaker operating at 8,000 amperes 13,200 volts had the same arcing time for natural frequencies from 3,900 to 200,000 cycles per second, but at higher currents arcing times increased when the natural frequency was over 30,000 cycles per second. The lowest frequency at which the maximum arcing could be reached was not determined, but on a laboratory circuit a natural frequency of about 190,000 cycles was heavily damped, indicating that the maximum arcing time had been obtained.

Relative Expense for Service Restoration With Different Types of Overcurrent Protection for Distribution Circuits

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THE combination of line sectionalizing in the main feeder, individual protection at branch-line junctions, and reclosing relays and breakers at the substation has been shown to provide a cumulative reduction in consumer minutes outage (minutes of outage per consumer per year) that no one of the methods can provide alone.[1] Branch protection proved to be of greater value than line sectionalizing.

However, in order to be of any real assistance in efficient system planning, such knowledge of the ways and means to improve service continuity must be combined with an understanding of the expense involved in restoring service for all combinations and types of protective equipment that are available. Such "restoration expense" involves the man-hours required to locate the fault, to make any necessary repairs on the line, and to restore service, and involves also the automotive miles which must be traveled in doing it. Naturally, initial costs must be included for an over-all consideration of the economics of overcurrent protection.

Calculations and Presentation of Data

Separate studies were made on two different setups of the distribution lines, namely, one for branch protection, as in Figure 1, and another for line sectionalizing with protective devices connected in series as in Figure 2. The assumptions in the appendix are basically identical with those used in the previous study for the calculation of consumer minutes outage.[1] The minor changes involve interpretations as to what portion of this outage time is for location, repair, and restoration of service, and where automotive mileage is required. Thus, it is possible to correlate directly the service outage value of different combinations and types of protective equipment from the previous study[1] with the values now being presented for the "restoration time" and the automotive miles traveled.

The following special terms are used throughout the paper:

"*Restoration time*" is the minutes per year spent by the trouble crew for all faults from the instant of notification of an interruption in service until all necessary repairs are made and service is restored.

"*Automotive mileage*" is the miles traveled by the trouble crew in performing the duties listed under "restoration time."

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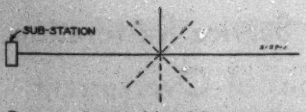


Figure 1. Individual branch-line protection added to 30-mile feeder

Branches located at center of feeder for average of even spacing along feeder

No. Branches	Total Length of Line: 1-Mile Branches	5-Mile Branches	10-Mile Branches
0	30	30	30
1	31	35	40
2	32	40	50
3	33	45	60
4	34	50	70
5	35	55	80
6	36	60	90

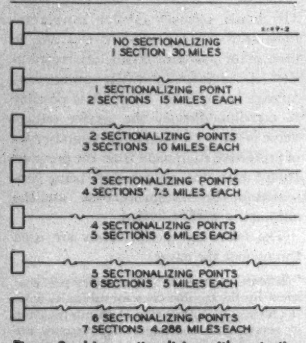


Figure 2. Line sectionalizing with protective devices connected in series on 30-mile line

"*Restoration expense*" is the total expense for "restoration time" and automotive mileage.

The "*yardstick*" is either the "restoration time" in minutes per year or the automotive mileage per year caused by "permanent faults alone" with no automatic or manual line sectionalizing and no branch protection.

Using the assumptions in appendix A, calculations were made to determine the "restoration time" and the automotive mileage traveled for each system setup, and the values are given as a percentage of the "yardstick" on the curves, Figures 5 to 12 inclusive, that is:

$$\text{Per cent} = 100 \times \frac{\text{Actual calculated values for specific system setup}^*}{\text{"the yardstick"}^*}$$

By making comparisons in terms of this percentage, we eliminate to some extent the effect of departures of actual practice from the assumptions employed in the study. Wherever such departures might affect the calculations, an attempt was made to be conservative in showing

* The calculated values and the "yardstick" may be in terms of either "restoration time" in minutes per year or automotive mileage traveled per year.

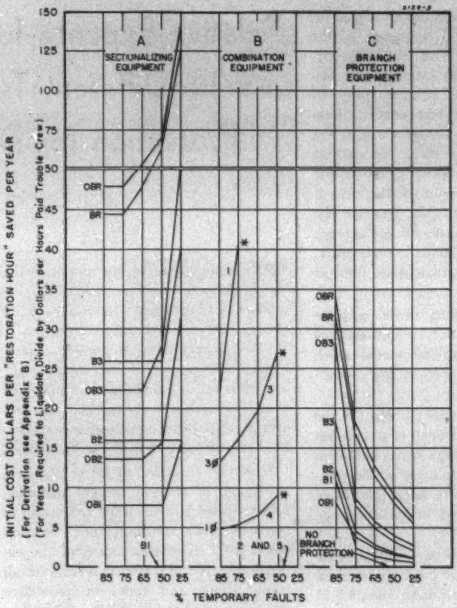


Figure 3. Curves showing cost per hour of "restoration time" saved per year to liquidate relative initial costs of protective equipment

Automotive mileage not included

Symbols defined in Figure 6

Column *A*. Curves for sectionalizing equipment show relative cost of making savings in "restoration time" over that required with single-element fuse cutouts

Column *B*. Curves for different combinations of equipment affording approximately equal service continuity show cost of saving in "restoration time" where made by higher cost equipment. *Such savings not made where curves not extended

Compare curve 1 with 2

Curve 1 for three resetting reclosers at sectionalizing points with three unprotected branches. Curves 2–8 for two-element reclosing cutouts, three at branches, five at sectionalizing points

Compare curves 3 and 4 with 5 (line sectionalizing only)

Curves 3 and 4 for three three-element reclosing cutouts three and one-phase circuits respectively

Curve 5 for five two-element reclosing cutouts one- or three-phase circuits

Column *C*. Curves for branch protection show the relative cost of savings in "restoration time" secured with different types and combinations of equipment

Observe that the cost of all reclosing equipment increases at a higher rate than the decrease in "restoration time" they provide

benefits for line sectionalizing or branch protection with the less costly line protective devices.

Known first costs are brought into the picture to determine the length of time required to liquidate any increased initial costs for equipment which provides savings in "restoration expense," as in Figure 3. (See also appendix B.)

The Curves

The data are given in curve form showing the percentage of the "yardstick" for varying arrangements of line protection. Figures 5 to 10 inclusive are for *branch protection*, and Figures 11 and 12 are for *line sectionalizing* with a number of protective devices connected in series. While these data may not fit a specific circuit exactly, they should be sufficiently close to be usable in planning the overcurrent protection on practically all distribution systems.

Actual Values for "Yardstick" Affect Comparisons

In addition to comparing the percentages given on the curves, it is important to consider also the value of the "yardstick" and the calculated values for specific cases in terms of the actual "restoration time" in minutes per year or the automotive mileage per year. Since we have assumed a constant number of total faults, the "yardstick," which is based on "permanent faults alone," is obviously lowest with 85 per cent temporary faults. It increases to a maximum at the 25 per cent temporary faults as shown in Table I. These values would increase or decrease respectively if extended beyond the 25 to 85 per cent range that was studied.

Much greater "restoration time," automotive mileage, and consumer minutes outage are required to locate, repair, and restore service with a permanent fault than just to restore service with a tem-

porary fault. Thus, as the percentage of temporary faults becomes greater, the "restoration time," automotive mileage, and consumer minutes outage caused by equipment opening on temporary faults increases less than the decrease in these values as caused by permanent faults. Because of this relationship, the calculated actual "restoration time" and automotive mileage for 25 per cent temporary faults are greater than that for 85 per cent temporary faults. This relationship is reversed when the calculated values are given as a percentage of the "yardstick" as on the curves, Figures 5 to 12 inclusive. This shift in relationship is important when evaluating the benefits secured by the use of the more effective device which usually costs more (see Figure 3).

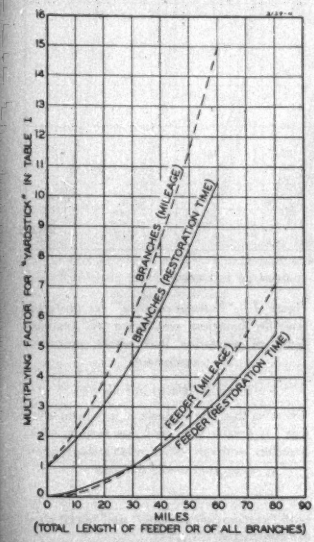


Figure 4. Conversion curves for determining "yardstick" with different lengths of feeder and total length of branches

How to use data:

1. Determine the multiplying factor
   (1). For the proper length of the feeder
   (2). For the total length of all the branches
2. Multiply the "yardstick" in Table I by the multiplying factor for the feeder
3. Multiply the corrected "yardstick" determined in item 2 by the multiplying factor for the branches

Observe that the "yardstick" is increased more by adding mileage to branches than by increasing the length of the feeder

Some Protective Devices Can Be Connected in Series in Greater Numbers Than Others

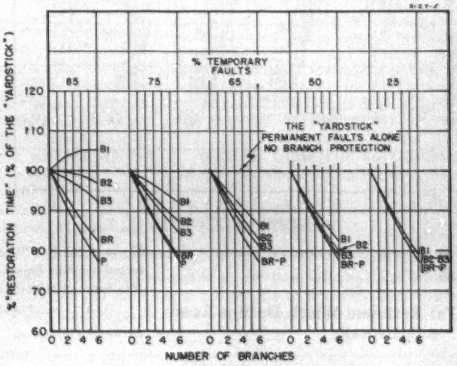
More two-element than three-element reclosing fuse cutouts can be connected in series and co-ordinated to provide about equal improvement in service continuity. Figures 11 and 12 indicate that the use of a greater number of two-element than three-element cutouts may increase the normal differences in "restoration expense" for these two devices at the higher percentages of temporary faults. However, when the difference in the initial costs of these two types of cutout is divided by the savings in "restoration expense," it shows that the cost per hour of "restoration time" saved per year by the use of the three-element design would be quite high, especially for three-phase circuits. For example, the use of two-element cutouts at five sectionalizing points and three-element cutouts at three sectionalizing points provides approximately the same service continuity. A comparison of these, as in Figure 3 (column *B*, curves 3, 4, and 5) indicates that from 6 to 13 years might be required to liquidate the extra cost of three three-element cutouts per phase on a three-phase 30-mile circuit, with a wage rate of one dollar per hour per man for a two-man crew.

A similar comparison is made in Figure 3 (column *B*, curves 1 and 2) to show the effect of the limitations in co-ordinating automatic resetting reclosers with fuses at branch junctions or at transformers. The use of three two-element cutouts to protect three branches added to a line sectionalized with the five two-element cutouts provides at least equal service continuity to that provided by three reclosers at sectionalizing points on the same line with the three branches unprotected. With 85 and 75 per cent temporary faults Figure 3 indicates that from 11 to 20 years respectively will be required to liquidate the additional cost of the reclosers with a wage rate of one dollar per hour per man for a two-man crew. With 65 and lower percentages of temporary faults the use of the two-element reclosing cutouts in the branches makes possible lower "restoration time" as well as a lower initial cost and a slight improvement in service continuity.

Figure 5. "Restoration time" for protected one mile branches employing nonreclosing or reclosing substation breakers and all available types of branch protective equipment

Symbols defined in Figure 6

Observe that a saving is made for all but single-element fuse cutouts when used with nonreclosing substation breakers at 85 per cent temporary faults



Effect of Nonreclosing and Reclosing Substation Equipment

With no line sectionalizing or branch protection, "permanent faults alone" are the only cause for sending out the trouble crew. The restoration of service after a temporary fault by manual or automatic reclosing of the substation breaker involves only the station attendant and thus the type of equipment employed has no effect on the "restoration time" or automotive mileage.

Combining Branch Protection and Line Sectionalizing

The cumulative effect on "restoration time" and automotive mileage of combining the protection of a number of short branches with line sectionalizing can be approximated from the data on the curves, Figures 5 to 12 inclusive. See appendix C for description of how to do this.

Where the circuit consists of two or more long branches, each branch should be studied separately from the standpoint of line sectionalizing and branch protection. Then the cumulative effect should be determined by adding or subtracting

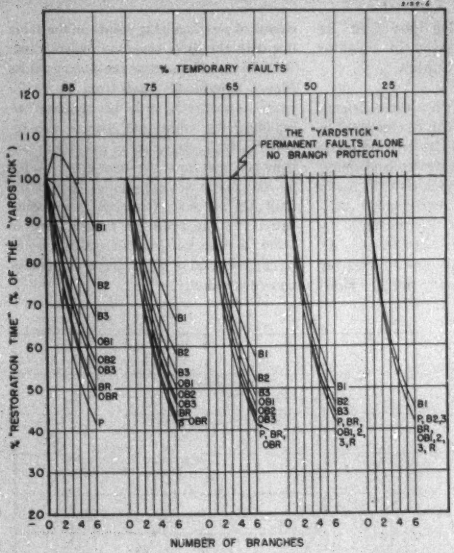


Figure 6 (left). "Restoration time" for protected five-mile branches employing all available types of substation and branch protective equipment

B = Nonreclosing or reclosing breaker at substation

OB = Overlapping reclosing breaker at substation, set for instantaneous tripping on first opening with all types of line protective equipment delayed to open only ahead of second opening of breaker

1 = Single-element fuse

2 = Two-element reclosing fuse

3 = Three-element reclosing fuse

R = Automatic resetting recloser

P = Permanent faults alone—all temporary faults cleared with only a momentary outage

(These are combined to show type of substation and line equipment employed)

Observe:

1. The major reduction in "restoration time" for "permanent faults alone" with the branches protected

2. The comparatively small increase in "restoration time" for outages caused by equipment opening on temporary faults

3. Single-element fuses provide the major portion of the reduction obtainable except at 85 per cent temporary faults

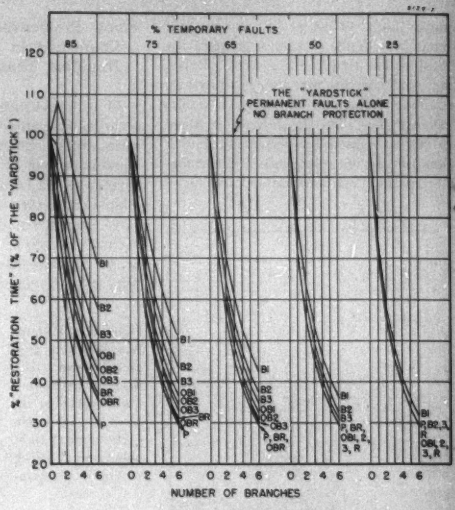


Figure 7. "Restoration time" for protected ten-mile branches employing all available types of substation and branch protective equipments

Symbols defined in Figure 6

Observe that the reduction in "restoration time" is greater with ten- than with five-mile branches with all other relationships being proportionally the same

the percentages as described in appendix C.

For Reclosers Which Do Not Reset Automatically

The conclusions drawn and the data in the curves for reclosing fuse cutouts apply to any type of apparatus with an equal number of reclosers and without the feature of automatically resetting after clearing a temporary fault.

Conclusions

Some general conclusions can be drawn from the study, although it is anticipated that the data will prove even more helpful in system planning when applied to the problems of specific circuits.

Substation Equipment

1. The substitution of reclosing for nonreclosing breakers at the substation, while improving service continuity, has no effect on the "restoration time" or automotive mileage (unless the substation attendant's time to manually reclose the breaker is classed as "restoration time").

2. Overlapping the substation reclosing protection with all line protective devices provides a major reduction in "restoration time" and automotive mileage. It is quite effective when combined with branch protective devices. (With such overlapping the breaker trips and recloses once without the branch or line protective device opening for all faults out to the ends of the line, and then the relay provides time delay so that the branch or line-sectionalizing protective device disconnects the faulted portion of the circuit ahead of the second tripping of the relay.)

3. Such overlapping protection of the entire line is the most economical of all system setups providing automatic reclosing, when both "restoration expense" and initial costs are considered.

4. Where such overlapping protection as in paragraph 2 reaches only part way out on the line, the decrease in "restoration time" and automotive mileage over a nonreclosing or reclosing breaker is only approximately one quarter of the decrease provided by overlapping the whole line.

Branch Protection Reduces Maintenance

1. Overcurrent protection of individual branches generally reduces "restoration time" and automotive mileage, even with short branches. The exceptions are with only a few or very short branches at high percentages of temporary faults where the actual number of minutes and miles are small (see Figures 5 to 10 inclusive).

2. The length of the branch has a major effect on the "restoration time" and automotive mileage.

3. Overcurrent protection of individual branches provides less reduction in terms of actual "restoration time" and automotive mileage at higher percentages of temporary faults than at the lower percentages.

4. The savings in "restoration expense" with branch protection are less likely to liquidate the initial cost of all types of overcurrent protective equipment at higher percentages of temporary faults than at

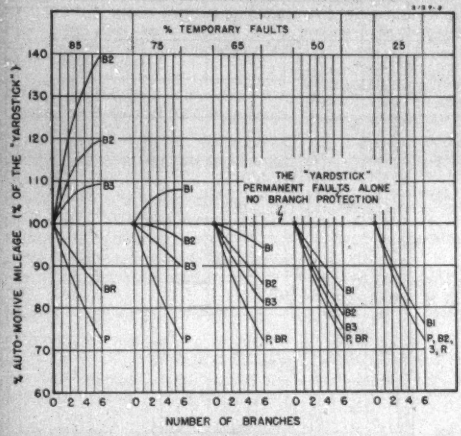


Figure 8. Automotive mileage for protection of one-mile branches employing nonreclosing or reclosing substation breaker and all available types of branch protective equipment

Symbols defined in Figure 6

Observe that the saving in automotive mileage for "permanent faults alone" is greater than the saving in "restoration time" (Figure 5). Also that the effect of outages caused by temporary faults is greater. However, the actual values for the "yardstick" in terms of automotive mileage is much less than for "restoration time"

the lower percentages, where the protective orbs of the substation relay and breaker includes the whole line.

5. Single-element fusing of branches, five miles and longer, is the most effective in saving sufficient "restoration time" and automotive mileage to liquidate the initial investment. Only a few years are required because of the comparative low first cost to the savings effected. For example, with 30 miles of single-phase branches on a 30-mile feeder and a wage rate of one dollar per hour per man for a two-man trouble crew, the liquidation would be effected in about 1 to 2.5 years. The exception is with 85 per cent temporary faults where the actual minutes and miles saved are too small to offset the initial cost of even single-element cutouts within a reasonable time.

6. Two and three-element reclosing fuse cutouts and automatic resetting reclosers provide reductions in "restoration time" and automotive mileage which are worthy of consideration. However, this saving is not proportionate with the increase in initial costs over that for single-element fuse cutouts.

7. Reclosing breakers at the substation which overlap single-element fuses at a num-

Figure 9 (below). Automotive mileage for protected five-mile branches employing all available types of substation and branch protective equipment

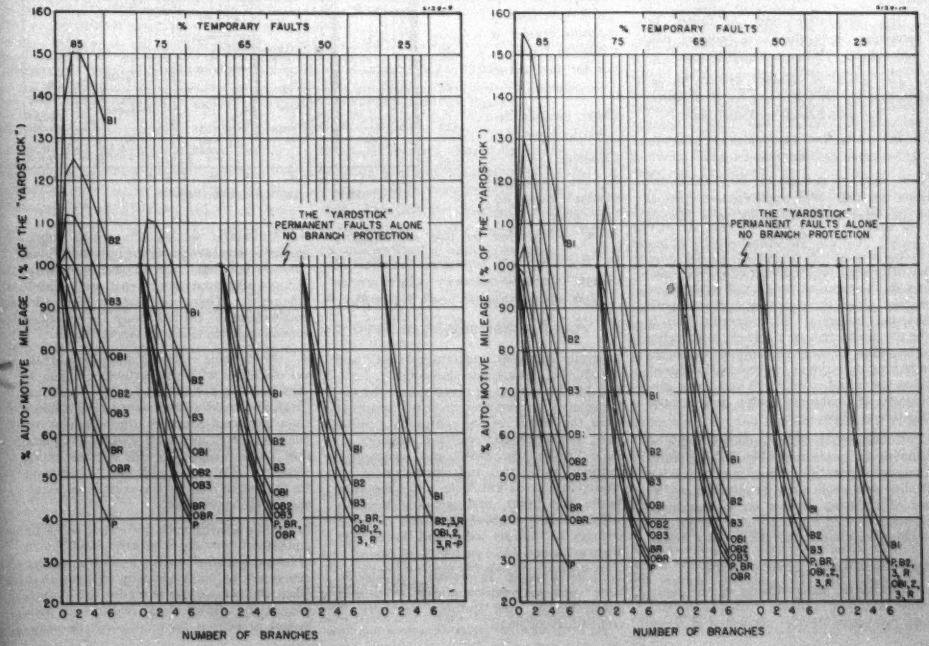
Symbols defined in Figure 6

Observe the same greater reduction in automotive mileage for "permanent faults alone" and the effect of outages caused by temporary faults as observed in Figure 8

Figure 10. Automotive mileage for protected ten-mile branches employing all available types of substation and branch protective equipment

Symbols defined in Figure 6

Observe that the reduction in automotive mileage is greater than with one- and five-mile branches (Figures 8 and 9), and that the effect of outages due to temporary faults is proportionately greater, especially at the higher percentages of temporary faults



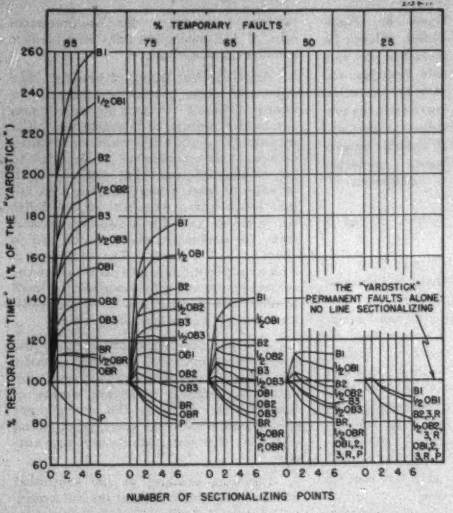


Figure 11. "Restoration time" with line sectionalizing employing all available types of substation and line overcurrent protective equipment

$\frac{1}{2}OB$ = overlapping reclosing breaker at substation, protection for only half of line

Other symbols defined in Figure 6

Observe:

1. The "restoration time" as caused by "permanent faults alone" is reduced only slightly by line sectionalizing
2. The effect of outages caused by devices opening on temporary faults is greater than with branch sectionalizing
3. Therefore, line sectionalizing generally increases "restoration time"

(This increase amounts to only about ten hours per year with single-element fuses at 85 per cent temporary faults on a 30-mile feeder)

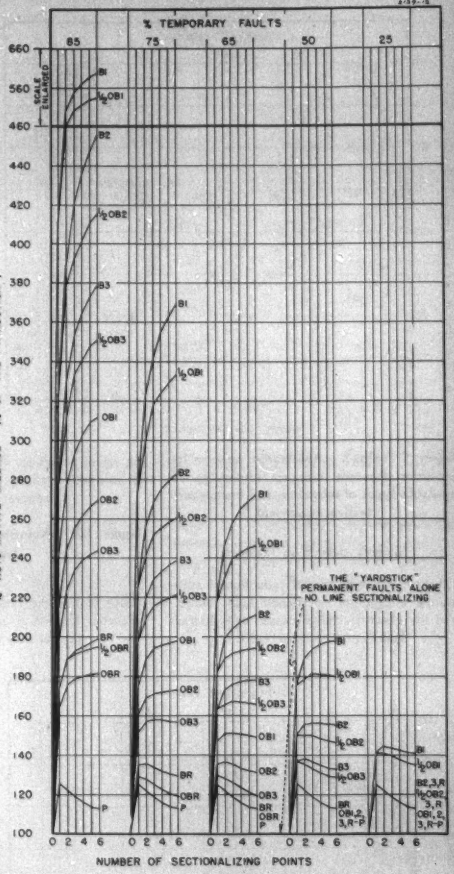


Figure 12. Automotive mileage with line sectionalizing employing all available types of substation and line overcurrent protective equipment

$\frac{1}{2}OB$ = overlapping reclosing breaker at substation, protection for only half of line

Other symbols defined in Figure 6

Observe:

1. The automotive mileage even for "permanent faults alone" is increased by line sectionalizing
2. As with branch protection, the effect of outages caused by temporary faults is greater than with "restoration time" (Figure 8)

ber of branch junctions provide more savings in "restoration time" and automotive mileage than three-element cutouts with reclosing breakers. This combination is almost as effective as single-element fusing of branches without overlapping protection in having the savings in "restoration time" offset the initial costs, at 75 and lower percentages of temporary faults, and is more effective at 85 per cent.

8. Consideration of the economic value of reducing the percentage of temporary faults appears to be justified. Such a reduction for the line as a whole might be obtained by the use of reclosing devices on a branch or branches having a much higher percentage of temporary faults than the line as a whole.

Automatic Line Sectionalizing

1. Automatic sectionalizing of the main feeder (and long branches treated as feeders) with protective devices connected in series generally increases "restoration time" and automotive mileage and thus must be justified by the savings in revenue and the improvement in customer good will resulting from the better service continuity. However, the automatic resetting reclosers reduce "restoration time" and automotive mileage, as do two and three-element reclosing fuse cutouts at 50 per cent temporary faults and lower, and reclosing breakers which overlap single-element and reclosing cutouts at 65 per cent and lower (see Figures 11 and 12).

2. The increase in actual "restoration time" and automotive mileage even with single-element fuse cutouts generally is comparatively small.

3. Automatic sectionalizing with single-element cutouts requires the most additional "restoration time" and automotive mileage but at a minimum over-all cost, see Figure 3, column 1. Therefore, sectionalizing with single-element cutouts may be justified economically in many instances.

4. Overlapping reclosing substation breakers combined with single-element fusing at sectionalizing points requires less additional "restoration time" and automotive mileage than sectionalizing with three-element reclosing cutouts and with a lower total first cost. This is especially true on three-phase circuits. (Only the additional equipment for the special relaying was considered necessary at the substation.)

5. Sectionalizing with automatic reclosing equipment provides a greater reduction in "restoration time" and automotive mileage compared to single-element cutouts than when the comparison is made with branch protection. However, as in the case with branch protection, the reduction in "restora-

tion time" and automotive mileage is not proportional with the increase in initial cost except possibly on lines appreciably longer than 30 miles.

Branch Protection and Line Sectionalizing Should Be Combined

The cumulative benefit obtained by combining branch protection and line sectionalizing should not be overlooked. Sectionalizing with equipment, the characteristics of which are such as to preclude branch protection, prevents the securing of major reductions in "restoration time" and automotive mileage.

Manual Line Sectionalizing

Manual line sectionalizing generally is employed where automatic protection has not been adopted. With manual sectionalizing "restoration time," automotive mileage, and consumer minutes outage are caused by "permanent faults alone" and thus are the same percentages of the "yardstick" at all percentages of temporary faults. Therefore, automatic sectionalizing and branch protection, which may cause outages on all or some temporary faults, are less likely to be justified over manual sectionalizing at the higher percentage of temporary faults (above 75 per cent) than is indicated when compared with the "yardstick." This is especially true on a feeder with relatively long branches where manual sectionalizing eliminates traveling out and back on a number of the branches in search of the fault.

Lowering of the Percentage of Temporary Faults Should Be Considered

1. Since outages caused by temporary faults make all types of equipment less efficient in attaining the minimum values for "permanent faults alone," consideration should be given to the economics of reducing the percentage of temporary faults, especially in the range above 75 per cent.

2. If the percentage of temporary faults is decreased, less costly equipment generally will provide equal or better service continuity with lower "restoration time" and automotive mileage.

3. A reduction in the percentage and thus the number of temporary faults on a specific system lowers the total number of faults and provides greater reductions in "restoration time" and automotive mileage than is shown in this study, where the total number of faults remain constant.

Use of Data for Continuing Expansion of Knowledge

Although over-all values of combining branch protection, line sectionalizing, and reclosing relaying at the substation as presented are based on a set of rigid assumptions, these data should facilitate more efficient planning of overcurrent protection on specific systems. It is hoped that these data will be extended, or if necessary, modified as the result of operating records secured in actual practice.

Table I. Actual Calculated Values⊖ for "Yardsticks" for Feeder Without any Branches† or Manual Line Sectionalizing

Values Decrease as the Percentage of Temporary Faults Increases

Units in Which Calculated Actual Values Are Expressed	Per Cent Temporary Faults				
	25	50	65	75	85
	Actual Values for Permanent Faults Alone*				
Consumer minutes outage per year	2,137.5	1,425	996.25	712.5	427.5
"Restoration time" in minutes per year	2,137.5	1,425	996.25	712.5	427.5
Automotive mileage per year	337.5	225	157.5	112.5	67.5

⊖ The values in this tabulation are based on a 30-mile feeder. To convert the values for longer or shorter feeders, use the multiplying factors as determined in Figure 4.

* These actual values will not apply exactly to any system, but the relationship shown should apply about proportionally. To determine actual "restoration time" and automotive mileage for any system setup, multiply the "yardstick" by the percentage for that setup as given on curves 5 to 12 inclusive.†

† The values in this tabulation do not apply directly to feeders with branches. Corrections can be made by use of the multiplying factors for the total length of all branches as determined from Figure 4.

Appendix A. Assumptions Employed in Mathematical Study

The same general assumptions employed in the study to determine the relative value of different types of overcurrent protection for distribution circuits in terms of service continuity[1] were used in continuing the mathematical study to check the effect on "restoration expense." All of the assumptions pertinent to the present study are tabulated below:

1. *The Distribution Lines Studied (Length of Lines)*

(a). In one part of the study one to six unprotected and protected branches, each one, five, or ten miles in length, were added at the mid-point of an unsectionalized 30-mile main feeder, increasing the total length of line, as in Figure 1. (The greater total length will increase the actual "restoration time" and automotive miles, but when these are expressed as a percentage of the "yardstick" (for "permanent faults alone" without branch protection), the effect of the length is cancelled. Thus the percentage shown on curves of Figures 5 to 10 inclusive for any system setup can be applied to any length of line or branches, if the "yardstick" is modified as directed in Figure 4. Connecting the branches at the mid-point provided an average for an even spacing of the branches along the feeder.)

(b). In the other part of the study, a 30-mile main feeder was broken up into from one to seven sections by zero to six overcurrent protective sectionalizing devices connected in series as in Figure 2.

2. *Equipment Employed.* Both studies included checking comparative results with overcurrent protection provided by:

(a). Substation breakers actuated by nonreclosing or automatic reclosing relays, and automatic reclosing relays which overlap all branch and line protective equipment so that the breaker trips and recloses once without the branch or line devices opening, and then provides time delay before the second tripping of the relay on more persistent faults; each combined with

(b). Sectionalizing or branch-line protection with single-element or two and three-element reclosing fuse cutouts or reclosers which reset automatically after clearing a temporary fault.

3. *Number and Type of Faults.* One fault per mile per year uniformly distributed with temporary faults equaling 25, 50, 65, 75, and 85 per cent of the total. (One fault per mile is probably somewhat high. Any lower value might have been used without changing the percentages used for comparison but would decrease the values for the "yardstick" in Table I and would change the values in Figure 3—decreasing these values for cost of "restoration" with line sectionalizing in column *A* and increasing the values for the cost to secure the savings with branch protection in column *C*).

4. *Attended Substation.* No "restoration time" was included for the substation attendant to close the station breaker or to notify the trouble crew. ("Restoration time" for temporary faults was zero, regardless of whether service was restored by manual or automatic reclosing of the station breaker. Thus, there is no difference in man-hours of "restoration time" or automotive mileage for nonreclosing or reclosing relays and breakers.)

5. *Trouble Crew.* Consisted of one man who was always available at the substation to start instantly with no time allowed for notification or preparation. (More often the crew consists of two men to meet safety requirements, but any multiple of one will have no effect on the percentages used in the presentation of the data. The actual "restoration time" in Table I can be multiplied by the exact number in the crew if over one, to make the values comparable with the utility's actual practice, see also the directions on Figure 3. Also, the crew is more likely to be out on the system, sometimes closer to and sometimes farther from the fault location, so that this assumption provided an average.)

6. *Time to Locate Fault, Make Necessary Repairs, and Restore Service.* The trouble crew:

A. With no branch protection or line sectionalizing (All temporary faults cleared when breaker locks open. Service restored by station attendant. Trouble crew required for "permanent faults only.")

(a). Traveled 15 miles per hour to the mid-point of the feeder as the average, and out to the mid-point

of each branch and back as the average for each branch.

B. With automatic line sectionalizing and individual branch protection

(*a*). Traveled 30 miles per hour to the sectionalizing point at which the protective device had opened. No time was allowed for examining sectionalizing or branch protective devices en route, as it was assumed that these would have indicating features visible from the car.

(*b*). Spent five minutes to climb the pole and to restore service if a temporary fault had caused the outage at the sectionalizing or branch protection point.

(*c*). Traveled 15 miles per hour to the mid-point of the branch or section on which the fault persisted. The mid-point provided the average for the uniform spacing of faults.

(*d*). Spent 30 minutes repairing a permanent fault. In a majority of cases the trouble crew will repair faults without calling for the assistance of the line crew, generally in less than 30 minutes. Where the services of the larger line crew are required, the time would generally exceed the 30 minutes average. This makes the values presented more conservative than actual practice.

(*e*). After repairing the fault:

1. No time was allowed to notify the substation attendant when he was required to close the breaker (although some time probably would be required for notification which would have increased the values of the "yardstick" Table I and the "restoration time" or automotive mileage for outages caused by temporary faults. This would have shown greater benefits for line sectionalizing and branch protection for reclosing cutouts and especially for automatic resetting reclosures).

2. The crew traveled 30 miles per hour to return to the sectionalizing or branch protective device to restore service.

3. No "restoration time" or automotive mileage was included after service was restored, since the crew might then be headed for another job to which the additional mileage and time would be charged.

7. *Service Restoration by First, Second, Third, and Fourth Reclosures* was assumed to be 50 per cent of the total number of faults for devices which reclose once, 65 per cent for those which reclose twice, 70 per cent for those which reclose three times, and 73 per cent for combinations which reclose four times (see Table IV in appendix of previous study[1]). This gives maximum advantage to three-element reclosing fuses and other multireclosing devices, as compared with two-element reclosing fuse cutouts, since these values for perfect operation are low for the first reclosing and high for the second as compared with operating experience. Some data show as high as 75 to 90 per cent restoration of service following the first reclosure.

8. *No Inspection With Reclosing Fuse Cutouts Was Assumed.* Because such inspection would have permitted refusing before an outage occurred, the data indicate only the minimum benefit for these devices.

(This benefit would be increased to a degree approaching that of the device that resets automatically, as such fuse renewal before the occurrence of an outage approaches 100 per cent. The percentage of such discovery and renewal is fairly high, because linemen and trouble crews are on the lookout for the indicating devices as they pursue their regular duties along the lines.)

Fuse renewal is accomplished in a few minutes while they are at the installation, without any traveling time or mileage as was included in the calculated values presented. Thus all reclosing fuse data are ultraconservative.

9. *The Protective Orbit of the Substation Breaker* (which is determined by minimum pickup current of the relay) included the whole feeder and all of the branches. In many instances distribution lines have outgrown this orbit. Consequently, the lower current individual protection of the branches and line sectionalizing on the otherwise unprotected portion may prevent burning down lines or annealing of the conductors. Such faults would require a long time to repair and might necessitate the assistance of the line crew. Conversely, this lower current protection may cause outages which might otherwise have burned clear. Depending on the type of equipment, after such outages service will be restored automatically or will require the trouble crew to go out to the sectionalizing or branch protection point in order to restore service. There would have to be a large number of such trips to equal the "restoration time" required for one case of putting back up lines burned down because of lack of protection.

Table II

Assumed Initial Costs Used for Figure 3	Cost Each†
Single-element fuse cutouts	$ 7.00
Two-element fuse cutouts	17.00
Three-element fuse cutouts	32.00
Automatic resetting reclosers	85.00
Additional relay equipment*	58.00

† These initial costs are approximately correct. Additional material other than the crossarm will be negligible as mounting hardware is furnished with the devices. Installation costs are not included as they will vary on different systems.

* It was assumed that induction-type reclosing relays and breakers are available.

No actual data are available on this relationship. However, it would appear that the "restoration time" in the area beyond the protective orbit of the station breaker would be reduced perceptibly by line sectionalizing and branch protection. This would decrease the higher "restoration time" and automotive mileage shown in this study for line sectionalizing, where the protective orbit encompassed the whole line, and would increase the savings shown for branch protection.

Appendix B. How to Determine the Cost Per Hour of "Restoration Time" Saved Per Year to Liquidate Relative Initial Costs of Protective Equipment

This is the method employed in figuring the values in Figure 3. It is applicable to the studying of automotive mileage costs as well (substitute mileage values for "restoration time" and proceed as described). Since with line sectionalizing the "restoration time" is increased over that for no sectionalizing, the comparison is made with the single-element cutout which requires the greatest "restoration time." Branch protection generally provides a reduction in "restoration time" from that with no protection and thus the comparison is made with the "yardstick" to determine the cost of securing this reduction.

Procedure

1. Determine the percentage for specific system setup from curves 5 to 12 inclusive, making additions for the cumulative effect of combining branch protection and line sectionalizing as described in the text.

2. Determine the actual "restoration time" for each specific system setup by multiplying the "yardstick" from Table I (modified if necessary for variations in length of the total line as described in Figure 4) by the percentage determined in paragraph 1.

3. Determine the difference in actual "restoration time" for the equipment being compared.

4. Determine the difference in initial costs of the equipment required for each system setup (see Table II).

5. Divide the difference in costs by the difference in "restoration time" to determine the cost per hour of "restoration time" per year.

6. Divide the values determined in paragraph 5 by the total wages per hour paid the trouble crew to determine the number of years required to liquidate the difference in initial cost (as determined in paragraph 4). Formulating this:

$$\text{Cost per unit† saved/year} = \frac{\left(\begin{array}{c}\text{unit† for less}\\ \text{effective device}\\ \text{(from item 2)}\end{array}\right)}{\text{Cost of more effective device*}} - \frac{\left(\begin{array}{c}\text{unit† for more}\\ \text{effective device}\\ \text{(from item 2)}\end{array}\right)}{\text{Cost of less effective device*}}$$

$$\text{Number of years to liquidate} = \frac{\text{cost/unit saved†/year}}{\text{dollars per hour paid trouble crew}}$$

Appendix C. How to Combine "Restoration Time" or Automotive Mileage Values for Branch Protection, Figures 5 to 10 inclusive, With Those for Line Sectionalizing, Figures 11 and 12

1. Where both cause "restoration time" or automotive mileage greater than 100 per cent (the "yardstick"), add to the percentage on one curve the percentage above 100 per cent on the outer curve, that is:

$$\text{Resultant per cent} = (\text{per cent on one curve}) + (\text{per cent} - 100 \text{ on other})$$

2. Where one system causes "restoration time" or automotive mileage greater than 100% and the other system less than 100 per cent, subtract from the first percentage the value of 100 − the second percentage, that is,

$$\text{Resultant per cent} = (\text{per cent which is greater than 100 per cent}) - (100 - \text{per cent which is less than 100 per cent})$$

* The cost value should be either the initial cost or the installed cost.

† The unit used may be in terms of restoration hours per year or automotive mileage per year.

Tests and Analysis of Circuit-Breaker Performance When Switching Large Capacitor Banks

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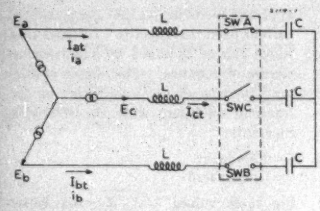
THE increased kilowatt burden on generation and transmission equipments—occasioned by the existing national emergency—calls for a reduction in the use of these equipments for generating and transmitting reactive kilovolt-amperes. When operating conditions permit the use of either capacitors or synchronous condensers, the relatively shorter production time of capacitors is making them more and more justifiable as a reactive source in the range of kilovolt-ampere ratings where economics might normally dictate a synchronous condenser.[1] At the present time the use of capacitors in banks up to 10,000 kva is being given increased consideration, and several installations having steps in this range have already been made.

With this growing use of capacitors, it is becoming increasingly necessary to apply adequate power circuit breakers to the task of switching these large banks, either totally or in steps, on and off the system. It has long been recognized that the job of switching capacitive circuits, such as long unloaded transmission lines, can become difficult, and it therefore logically follows that both the duty on the breaker and its effect on the system during switching of large capacitor banks should be investigated.



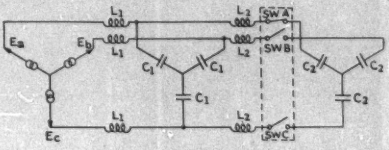


Figure 1. Transient-analyzer circuit for determining effects of sequential pole closing

(a). Total capacitor bank energized

(b). Capacitor bank energized against already energized bank. L_1 is inductance of breaker and bus work between banks

When a capacitor bank is energized, a large component of natural frequency current initially flows in addition to the normal-frequency circuit current. If the bank is energized against an already energized bank, even larger natural-frequency equalizing currents may flow through the breaker. The effect of these currents must be evaluated.

When a capacitor bank is de-energized, larger than normal system voltages may exist across the breaker contacts because of the trapped charge on the capacitor. This may impose a greater than usual task on the breaker dielectric to interrupt with a minimum of restriking, and if restriking occurs, there may be voltage stresses above normal on the capacitor units as well as on the other connected equipment.

This paper offers an analysis of the problem together with test results on full-scale and miniature capacitor banks. Certain conclusions are drawn relative to the duty on and selection of breakers for this service.

Summary of Conclusions

A total of 338 tests on oil blast and Magne-blast types of power circuit breakers in the voltage class up to 15 kv and up to 250,000 kva short-circuit capacity, have been made. The results of this investigation, coupled with the analytical treatment contained in this paper, have allowed the following conclusions to be reached:

1. Based upon transient-analyzer analysis, it is shown that under the most pessimistic conditions of controlled restrike, abnormal circuit overvoltages can occur in de-energizing capacitors. This agrees with the results of other investigations[2] covering fault clearing on circuits containing capacitance.

2. Full-scale tests demonstrate that *standard* oil-blast breakers in the above classification recover their dielectric strength sufficiently fast to switch capacitor banks up to at least 10,000 kva without creating abnormal overvoltages.

As the capacitor kilovolt-amperes is further increased, a point is reached where restriking becomes more probable. Whether abnormal overvoltages appear or not is then determined by the randomness of the restriking phenomena and the inherent damping characteristics of the associated circuits.

3. Full-scale tests show that the high series resistance in the arc chute of the Magne-blast type of breaker, when restriking occurs, prevents the abnormal overvoltages usually associated with restriking phenomena. This is evidenced by the successful interruption of 31,400 kva—3,400 amperes at 5,350 volts.

4. Full-scale tests demonstrated that the peak values of transient equalizing currents upon energizing capacitor banks are within the values given by the equations presented in this paper and in reference 2.

5. The short-circuit interrupting rating of a breaker need not be increased by the

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3. Where both systems cause "restoration time" and automotive mileage less than 100 per cent (the "yardstick"), subtract from the percentage on one curve the value of 100 — percent on the other curve, that is,

Resultant per cent = (per cent on one curve) — (100 — per cent on other curve)

To determine the actual "restoration time" and automotive mileage multiply the "yardstick" in Table I, modified as directed in Figure 4, by the resultant percentage.

Reference

1. RELATIVE VALUE OF DIFFERENT TYPES OF OVERCURRENT PROTECTION FOR DISTRIBUTION CIRCUITS, G. F. Lincks. AIEE TRANSACTIONS, volume 61, 1942, January section, pages 19-26.

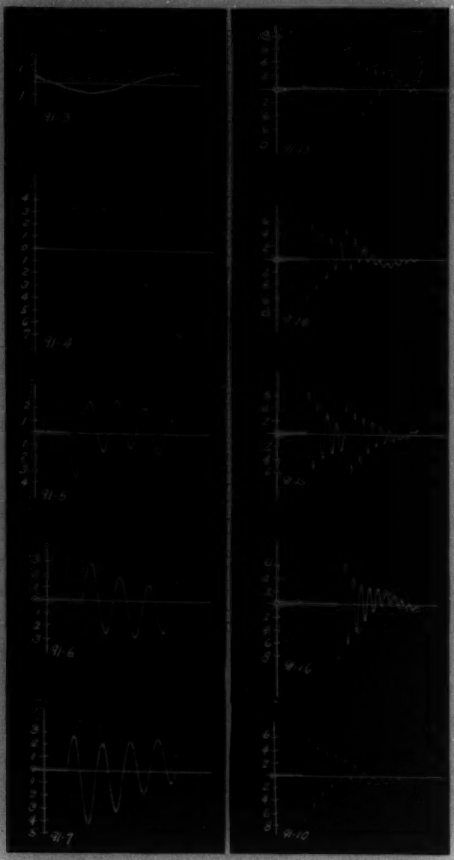


Figure 2. Transient-analyzer oscillograms showing currents obtainable when energizing capacitors

Current calibration in times normal steady-state capacitor current

91-3 One cycle of normal magnitude, fundamental frequency capacitor current

91-4 Inrush current, phase *b*, on energizing capacitor bank of Figure 1a. Switch *b* closed at E_{ab} maximum; switch *c* closed 36 degrees later for maximum I_b

91-5 I_a for condition of 91-4

91-6 I_c for condition of 91-4

91-7 Inrush current, phase *b*, on simultaneous energizing of capacitors of all three phases of Figure 1a at the instant that makes I_b maximum

91-10 Inrush current, phase *b*, on simultaneous energizing of capacitors of all three phases of Figure 1b at the instant that makes I_b maximum

91-13 Inrush current, phase *c*, on energizing capacitor bank of Figure 1b. Switch *b* closed at E_{ab} max; switch *c* subsequently closed to give I_c a maximum

91-14 I_b for condition of 91-13

91-15 I_a for condition of 91-13

91-16 Same as 91-13, except switch *b* closed 10 degrees ahead of E_{ab} max
Switch *c* subsequently closed to give I_c a maximum

proximity of a capacitor bank on the bus side.

6. All tests made under various energizing and discharging conditions—many of which are presented in this paper—showed that the peak values of transient current obtained were not harmful to the breakers tested. The maximum value reached was 52,000 amperes.

The Energizing Problem

Energizing a Single Bank

It has been shown[3] that the maximum inrush current, neglecting system capacitance and damping, when energizing a single capacitor bank at the peak of the voltage wave is given by

$$I_{max} = I_b(1+\sqrt{X_c/X_L})$$

where

I_b = peak value of steady-state capacitor current

X_c = reactance of capacitor bank

X_L = system reactance viewed from capacitor location

Since a switching problem is being considered, it may be appropriate to express inrush currents to capacitors in terms of the short-circuit current available at the capacitor location. Doing this, the above expression may be written as

$$I_{max} = I_c(1+\sqrt{I_{sc}/I_c})$$

where the subscripts stand for the capacitor rated current and the short-circuit currents—as initialed. All currents are expressed in peak values. This amounts to approximately 2,500 amperes for a 10,000-kva bank of capacitors closing on to a 13.8-kv system capable of delivering 250,000-kva short circuit.

These expressions hold for each phase of a wye-grounded bank on a grounded system. In wye floating neutral or delta-connected banks, however, the initial individual phase currents are a function of the order of pole closing. And since breakers probably do not close their contacts simultaneously, this case was investigated to determine if larger currents than those indicated by the above expression, could be obtained.

The analysis of this case*—as given in appendix B—indicates that the maximum current from this effect is 1.15 times that which can be obtained by simultaneous closing of contacts. The circuit of Figure 1(a) was set up in miniature on the transient analyzer[4] with the following constants:

$L = 0.234$ henry

$C = 1$ microfarad

For these values $\sqrt{X_c/X_L} = 5.5$ hence I_{max} by above equation should be no greater than $1+5.5 = 6.5$ times normal. Oscillographic results are presented in Figure 2. For the equivalent single-phase or simultaneous closing case, oscillogram 91-7 shows a peak inrush current in phase *b* of 4.5 times normal. Oscillogram 91-4 shows I_b for switch *b* closed at E_{ab} a maximum and switch *c* closed 36 degrees later to give I_b a maximum. This maximum of approximately 6.0 times normal, and the 4.5 above indicates that even the small damping in the miniature setup greatly reduces the maximum obtainable.

Energizing a Bank Against an Already Energized Bank

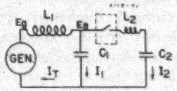
In this case the energized bank discharges into the oncoming bank through the relatively small impedance between them. The resulting large equalizing current of short duration oscillates at the high natural frequency determined by the value of series capacitance of the two banks, and the inductance of the connections between them.

Equations for determining these currents have already been given[3] for simul-

* A time of at least 1/4 cycle of natural frequency constitutes a severe nonsimultaneous pole-closing condition from this standpoint.

Table I. Single-Phase Closing Tests When Energizing a Bank Against an Already Energized Bank

No	X_L Ohms	C_1 Micro-farads	C_2 Micro-farads	E_R RMS Volts	I_1 RMS Amperes	I_T RMS Amperes	I_2 Peak Test	I_2 Peak Calculated	Closing Angle Degrees	Natural Frequency (Cycles Per Second)	L_2 Millihenry Calculated from Test
Oil-Blast Breaker—250,000 Interrupting Kva											
1	6.72	17.7	17.7	15,150	101	210	*	8,940	68	8,100	0.0436
2	3.72	35.4	35.4	16,500	220	400	*	15,800	72	6,400	0.0349
3	2.12	70.2	66.7	15,130	400	827	13,000	18,200	88	(Figure 3) 3,900	0.0487
4	0.42	440	417	5,850	960	2,030	15,400	17,700	89	1,750	0.051
5	2.12	70.2	66.7	14,380	380	786	640	1,250	4	4,100	0.0440
6	0.92	440	417	7,800	1,280	3,200	1,380	2,000	6	1,300	0.0700
Magne-Blast Breaker—150,000 Interrupting Kva											
7	0.42	440	417	5,850	960	2,400	12,400	14,400	65	1,440	0.051
8	0.42	440	417	5,850	960	2,400	14,800	18,220	90	(Figure 4) 1,650	0.051
9	0.42	440	417	5,850	960	2,500	5,700	9,250	34	1,500	0.0525
10	0.42	440	417	5,850	960	2,400	10,600	11,400	51	1,330	0.067

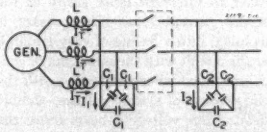


* Natural frequency beyond vibrator response.

Table II. Closing Tests Energizing a Three-Phase Delta Bank Against an Already Energized Delta Bank

Tests Were Made at 5,400 Volts

No	X_L Ohm L-N	C_1 Microfarads L-L	C_2 Microfarads L-L	I_1 RMS Before Closing	I_2 Peak During Closing Pole$_1$	Pole$_2$	Pole$_3$	Natural Frequency (Cycles Per Second)	Per Cent Rise Before Closing	Per Cent Rise After Closing
1	0.805	133	126	540	8,800	9,500	3,800	1,800	16	31.0
2	0.805	133	126	540	8,000	9,100	2,700	2,000	16	31.0
3	0.805	133	126	540	8,400	9,300	2,700	1,800	16	31.0
4	0.805	133	126	540	8,000	8,500	5,100	2,000	16	31.0



taneous pole closing, so will not be repeated. The case of sequential pole closing, however, was set up in a miniature circuit of Figure 2, using the following constants:

L_1=0.234 henry C_1=3 microfarads
L_2=0.048 henry C_2=1 microfarad

(L_1 and L_2 in per unit of the total capacitive kilovolt-amperes are 0.133 and 0.027, respectively)

The equalizing current on energizing C_2 was measured by means of the cathode-ray oscillograph. A comparison of the effect of simultaneous closure of the three poles of the switch with that of sequential closure (with the interval between pole closures controlled to give maximum current) is given in Figure 2 by oscillograms 91-10 and 91-13. It will be noted that the first natural-frequency current peak is nearly the same (eight times normal) in the two cases, indicating that sequential closing for the adjacent bank case has less effect on current maximum than in the single bank case.

Figure 3a. Oscillograms showing the equalizing currents associated with the energizing of an adjacent bank with an energized bank on the bus

See Figure and test 3 in Table I

B—Bus capacitor current, I_1 *C*—Cathode ray oscillograph relay trip
D—Oncoming capacitor current, I_2 *E*—Line current, I_T *F*—Breaker travel

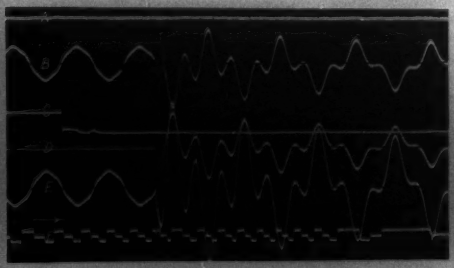
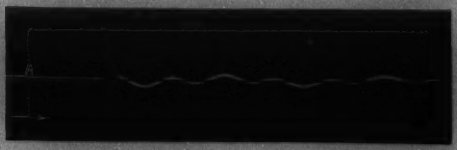


Figure 3b. Oncoming capacitor current of Figure 3a

See test 3 of Table I

Oscillogram 91-16 shows the effect of closing the second switch *b* ten degrees ahead of the time when the voltage across it would be a maximum. The same maximum current (in phase *c*) was obtained



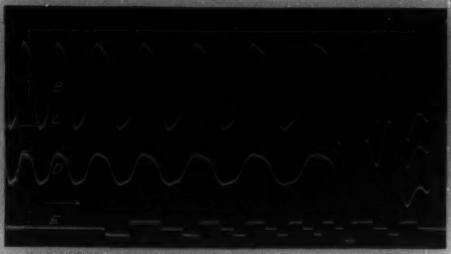


Figure 4a. Oscillogram showing the currents associated with the energizing of a 417-microfarad bank with a 440-microfarad bank on the bus

See test 8 in Table I

B—Bus capacitor current, I_1
C—Oncoming capacitor current, I_2
D—Line current, I_T
E—Breaker travel

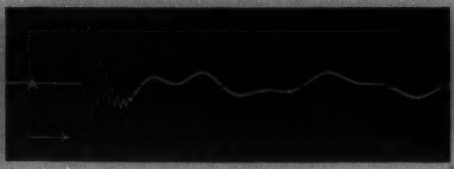


Figure 4b. Oncoming capacitor current of Figure 4a

See test 8 in Table I

by varying the angle of closing the last switch.

Full-Scale Tests

Tables I and II list a few of the typical test data recorded during the energizing tests. The test arrangement was designed to have small inductances in order to obtain maximum currents. In spite of this, the maximum current measured was below 20,000 amperes. In none of these tests were current-limiting impeders used. Figures 3, 4, and 5 are typical oscillographic records of the energizing phenomena with cross reference to Tables I and II giving the numerical values.

Discussion

The data in Tables I and II show the equalizing current values of adjacent single-phase and three-phase bank energizing. The largest adjacent bank energizing currents are well below the nominal values of current which these breakers are normally called upon to handle. The successful performance of the breakers under these conditions, together with the results presented in the section on "Capacitor Discharge During Short Circuit," shows that the "closing-in" duties of standard breakers constitute a very minor problem. The equalizing currents are high-frequency (1,000 to 5,000 cycles) highly damped discharges, producing negligible distress either as contact burning or as a delaying mechanical impulse to the closing breaker contact. Figure 6 shows an enlarged portion of the breaker contacts after 34 closing tests.

The De-energizing Problem

The initial voltage *across* a circuit breaker following the interruption of a capacitor circuit is zero, since the capacitor on one side holds the same crest voltage that existed on the bus side of the breaker at and immediately following current zero. This permits any circuit breaker to interrupt quite easily at the first arc current zero. The breaker is thus lulled into a feeling of easy triumph over the circuit with the minimum of contact separation when suddenly—with the cyclic reversal of system voltage—double instead of zero voltage appears across the open breaker just one-half cycle following the interruption. If the breaker withstands this double voltage without restriking, then and not until then can the circuit be considered as cleared. If, on the other hand, the circuit is restruck as the voltage approaches this cyclic reversal, then a series of events is possible which must receive special consideration.

In counterdistinction to capacitive interruptions, the current in inductive circuits is interrupted at each current zero, whereupon the double-voltage-recovery transient is immediate, and circuit interruption is either achieved, or the arc is restruck for another half cycle to repeat the attempt under similar conditions at the next current zero. Thus the insulation is permitted to build up between the separating contacts until such a point is reached that the circuit is cleared without accumulative voltage distress. (There

Figure 6. Circuit breaker contacts following a total of 34 closing tests in which an adjacent bank was energized with an energized bank on the bus

Typical tests are shown in Table I

Figure 5 (below, right and left). Oscillograms showing the phenomena in two phases associated with the closing on a 4,150-kva delta bank with a 4,400-kva bank on the bus

See test 4 of Table II

A—Capacitor current, I_1
B—Line-to-line voltage
C—Bus side capacitor current, I_2
D—Breaker travel

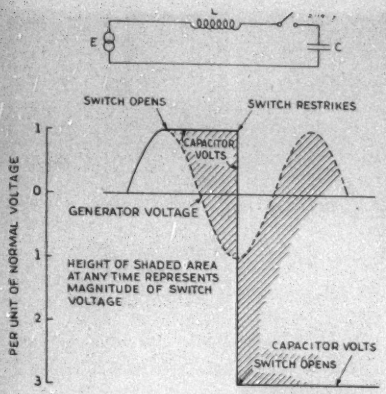
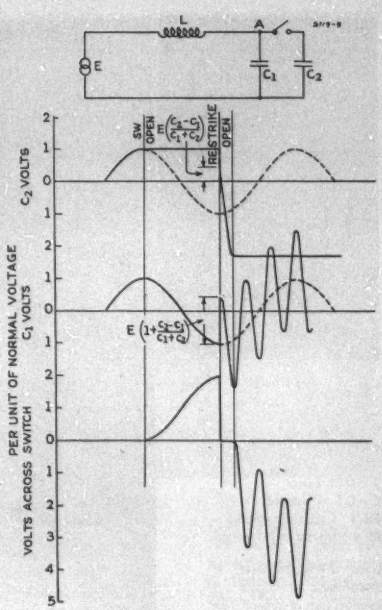


Figure 7 (left). Case I—De-energizing grounded neutral capacitor bank

Total capacitance switched—shows basis of analysis

Figure 8 (right). Case II—De-energizing grounded neutral capacitor bank

Part of capacitance unswitched $C_1/C_3 = 0.2/0.5$



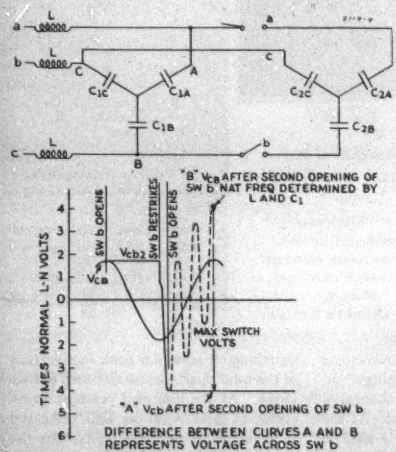


Figure 9. Case VIII—De-energizing ungrounded neutral three-phase capacitor bank with part of capacitance unswitched

Second switch to open

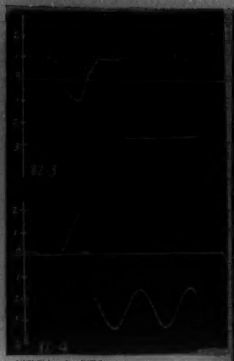
are however special cases of inductive circuits where abnormal restriking overvoltages can occur.[3] The effects of the restriking phenomenon on the capacitor switching problem are discussed under the section "Capacitor Discharge During Short Circuit.")

A comparison of these phenomena indicates that the interrupting capacity of standard breakers on capacitive circuits may be limited as described in this paper. The limitations are not so much in the ability of the breakers to eventually clear the circuit as they are in the desirability of limiting overvoltages on the system to safe values.

At this point, it is desirable to point out that the considerations contained in this paper deal with capacitor banks of high capacitive kilovolt-amperes, and in no way should the discussion presented here be construed to apply to circuits which contain relatively small capacitors—as for example, capacitors for the protection of electric equipment from lightning or switching surges and the lower-voltage equipments in industrial plants. In fact, the phenomena presented here are more akin to the phenomena of the interruption of line-charging current on high-voltage transmission systems. The two problems are identical in every major respect and differ only in degree. The capacitive kilovolt-amperes to be interrupted on high-voltage lines is usually large. As with the capacitor bank, interruption takes place easily at the first current zero in the arc, thus leaving the entire line charged to the crest value of generated voltage. As the generated voltage reverses on the bus side, double voltage appears across the switch. The breakers required to interrupt this line-charging current are inherently large, and although the contact velocity on parting is considerably larger than in the smaller breakers, it is not larger in proportion to the voltage. It follows that the voltage to appear across the open pole one-half cycle after contact parting is therefore much greater on the high-voltage systems. This fact, together with the large kilovolt-amperes to be interrupted explains why these interesting phenomena were first found on the high-voltage transmission systems. The trend toward large capacitor banks tends to project the above phenomena into the lower-voltage systems, not by reason of voltage, but because the heavier currents to be interrupted act to weaken the arc gap one-half cycle after parting, thus permitting the gap voltage on the reversal of bus voltage more easily to produce a restrike. The studies presented in this paper reveal the degree to which these phenomena are important to the lower-voltage switching equipments.

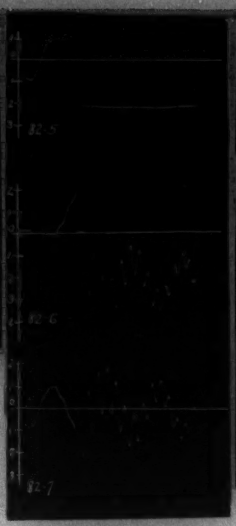
Analysis

Tests have been made on the transient analyzer[4] to determine the maximum magnitude of transient overvoltage that would be obtained when switching off various connections of capacitors, with the assumption that the circuit-opening mechanism would restrike once. The capacitor switch was opened at a funda-



Case I

Case I—Single-phase or three-phase grounded capacitor, total capacitance switched
L=0.85 henry
C=0.5 microfarad
82-3 Capacitor voltage
82-4 Voltage across switch

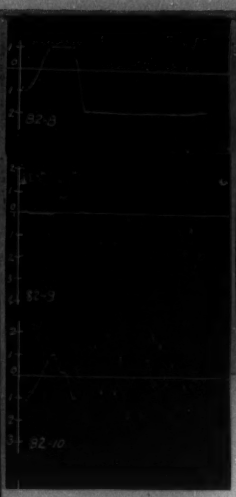


Case II

Case II—Single-phase or three-phase grounded capacitor, part of capacitance switched
L=0.85 henry
C_1 (unswitched)=0.2 microfarad
C_2 switched=0.5 microfarad

82-5 Capacitor voltage
82-6 Voltage across switch
82-7 Unswitched capacitor voltage

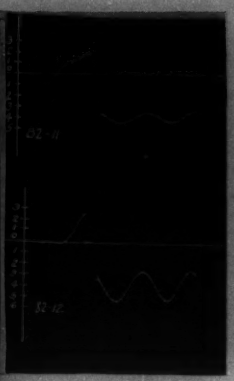
Case IV—Same as case II, except L=1.67
C_1=0.2 microfarad



Case IV

C_2=0.5 microfarad 82-8
82-9
82-10

Case V—Three-phase ungrounded neutral capacitor, total capacitance switched—first switch to open, phase a
82-11 Voltage of switched capacitor to ground
82-12 Voltage across first switch to open



Case V

Figure 10. Transient-analyzer oscillograms showing voltage obtainable when de-energizing capacitors, for various connections and assuming one restrike at peak of voltage wave

All voltage calibrations in times normal of normal L-N crest voltage

mental frequency current zero and reclosed by means of a synchronous switch at the subsequent recovery voltage maximum to represent a restrike. Although this switching procedure does not involve the randomness present in the circuit-breaker performance, it gives the highest possible magnitudes of both switch and capacitor voltage.

Table III presents the results of these tests, giving the peak switch and capacitor volts for the condition of no restrike and one restrike. Figures 7 through 9 show some of the connections tested and a "free-hand" graphical analysis of the voltages. These supplement the oscillograms in Figure 10.

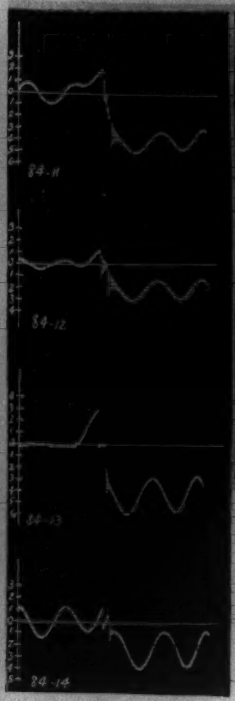
Figure 7 shows the fundamentals by which these transient overvoltages are obtained. At a current zero (peak of the voltage wave) the switch is opened, whereupon a full charge remains on the capacitor. The fundamental frequency system voltage moves onward until it is a negative maximum resulting in a switch voltage of twice normal. A restrike is permitted at this point, and the capacitor voltage changes to system voltage on the circuit natural frequency and overshoots (neglecting resistance damping) an amount equal to its attempted change, or to -3 times normal, as shown. At the first subsequent current (largely natural frequency) zero, the switch is reopened, and the charge of -3 times normal remains on the capacitor.

Figure 8 shows a similar analysis for switching off part of a bank (65 per cent of the total in all these tests) with one restrike. At the time just previous to restrike, C_1 is at -1.0 per unit volts and C_2 is at $+1.0$ per unit volts. In the transient-analyzer tests there was no intentional current limiter between C_1 and C_2; hence immediately upon restrike the charge on C_1 and C_2 equalized to a value

Table III. Transient Analyzer De-energizing Tests

Case No*	Condition	Peak Capacitor Volts to Ground		Peak Switch Volts	
		No Restrike	One Restrike	No Restrike	One Restrike
Grounded Neutral					
I	Switching 0.5-microfarad bank	1.0	3.0	2.0	4.0
II	Switching 0.5-microfarad bank, 0.2 microfarad unswitched	1.0	2.4	2.0	4.8
III	Same as I, L_1 changed from 0.85 to 1.67 henries	Similar to case 1			
IV	Same as II, L_1 changed from 0.85 to 1.67 henries	Similar to case 2			
Ungrounded Neutral					
V	Switching 0.5-microfarad bank, 1st phase	2.0	5.0	3.0	6.0
VI	Switching 0.5-microfarad bank, 2nd phase	2.6	6.0	3.46	6.6
VII	Switching 0.5-microfarad bank, 0.2-microfarad unswitched 1st phase	2.0	3.7	3.0	6.1
VIII	Switching 0.5-microfarad bank, 0.2-microfarad unswitched 2nd phase	2.5	6.0	3.46	8.2
IX	Same as VII, neutrals of capacitors connected	1.6	3.3	2.6	4.3

* See oscillograms, Figure 10.



Case VI

Case VI—Same as case V. Second switch to open (*b* phase)

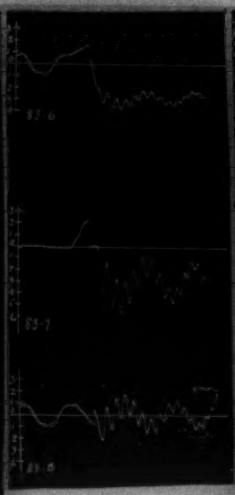
84-11 Voltage of capacitor being switched (*b*) to ground

84-12 Voltage of capacitor already switched (*a*) to ground

84-13 Voltage across switch *b*

84-14 Voltage across switch *a*

Case VII—Three-phase ungrounded neutral capacitor, part of capacitance switched—first switch to open



Case VII

83-6 Voltage of switched capacitor to ground

83-7 Voltage across first switch to open

83-8 Voltage of unswitched capacitor on phase *a* to ground

Case VIII—Same as case VII. Second switch to open (*b* phase)

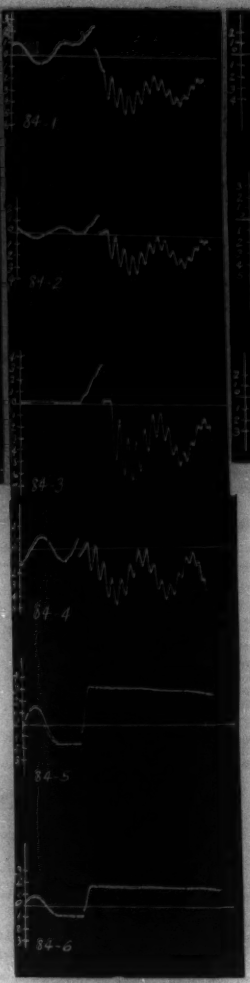
84-1 Voltage of capacitor being switched (phase *b*) to ground

84-2 Voltage of capacitor already switched (*a*) to ground

84-3 Voltage across switch *b*

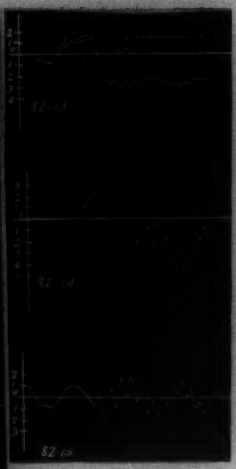
84-4 Voltage across switch *a*

84-5 Voltage V_{bc} on opened capacitors



Case VIII

84-6 Voltage V_{ac} on unswitched capacitors



Case IX

Case IX—Same as case VII. First switch to open, capacitor neutrals connected. (Comparison with case VII shows effect of unswitched capacitors in holding down neutral displacement of switched capacitors)

82-13 Voltage of switched capacitor to ground (phase *a*)

82-14 Voltage across first switch to open

82-15 Voltage of unswitched capacitor on phase *a* to ground

Figure 10 (continued.) Transient-analyzer oscillograms showing voltages obtainable when de-energizing capacitors, for various connections and assuming one restrike at peak of voltage wave

All voltage calibration in times normal of normal *L-N* crest voltage

given by $E(C_3-C_1)/(C_1+C_3)$ and then oscillated to a value given by $-E(C_1+3C_3)/(C_1+C_3)$. An analytical determination of this expression is given in appendix B.

The constants used for these transient-analyzer tests—in *L-N* values—were:

System inductance $L=0.85$ henry except cases 3 and 4, $L+1.67$ henries

Capacitance switched $C_3=0.5$ microfarad

Capacitance unswitched $C_1=0.2$ microfarad

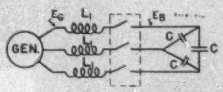
The most severe overvoltage across the switch on de-energizing occurs when switching off part of an ungrounded wye (or delta bank) and when the second phase clears. This is shown by Figure 9 (case VIII). The capacitor overvoltage is equal to that obtained when switching all of the bank.

Full-Scale Tests

Analysis shows—Table III—abnormal voltages are possible with one restrike under the most pessimistic conditions. Full-scale tests were made to determine practical conditions obtaining.

Table IV. De-energizing Tests—Three-Phase Ungrounded Capacitor

No	E_G Volts L-L	X_L Ohms L-N	C Microfarads L-L	Capacitive Kva Switched	E_B Peak Opening L-G	E_B/E_G L-G Peak Opening	I_{RMS} Opening Amperes	Remarks
Oil-Blast Breaker—150,000 Interrupting Kva								
1	4,000	0.23	300	6,330	4,000	1.23	845	No disturbance—cleared
2	4,000	0.23	600	15,100	4,100	1.26	1,850	
3	4,000	0.23	600	15,100	4,000	1.23	1,850	
Oil-Blast Breaker—250,000 Interrupting Kva								
4	14,500	3.38	17.7	4,850	16,660	1.40	180	No disturbance—cleared
5	14,500	3.38	17.7	4,850	16,600	1.40	180	
6	14,500	3.38	34.4	10,800	16,000 Figure 12	1.35	375	
7	14,500	3.38	34.4	10,800	19,400	1.64	375	
8	14,500	3.38	34.4	10,800	19,000	1.61	375	
Magne-Blast Breaker—150,000 Interrupting Kva								
9	4,000	0.23	600	15,200	5,000	1.54	1,850	Moderate report—cleared
10	4,000	0.23	300	6,300	6,000	1.85	845	
11	4,000	0.23	975	31,400	4,900	1.51	3,400	
12	4,000	0.23	975	31,400	5,000	1.54	3,400	
Magne-Blast Breaker—250,000 Interrupting Kva								
13	5,400	0.47	259	11,400	6,000	1.37	1,050	Moderate report—cleared
14	5,400	0.47	259	11,400	6,500 Figure 11a	1.49	1,050	
15	5,400	0.47	259	11,400	5,100	1.17	1,050	
16	5,400	0.47	259	11,400	5,400	1.23	1,050	



conditions, which again helped to plan and analyze the full-scale program. The miniature setup allowed the following conclusions to be drawn:

1. Effect of circuit constants (L and C). If the entire bank is switched, the magnitude of the switch or capacitor voltage is not appreciably affected by the system constants provided that the circuit natural frequency is not less than approximately 180 cycles. (Refer to cases I and II of Figure 10.)

2. Presence of an unswitched bank. If part of the bank remains unswitched, the capacitor and switch volts are the same as the condition of total bank switched, if no restrike occurs. If restrike occurs, the smaller the bank unswitched, the larger the switch voltage, the limit being a very small unswitched capacitance for which a somewhat greater voltage may be obtained than for the case of absolutely no unswitched capacitance. Table I summarizes quantitative results.

3. Effect of grounding. Grounding the capacitor bank on a grounded system results in the lowest switching overvoltages, as may be seen by comparing the values of the grounded and ungrounded cases of Table III.

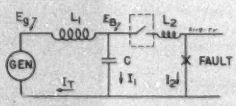
4. Effect of interconnecting neutrals of switched and unswitched banks. The unswitched bank under this condition has the tendency of holding the neutral of the switched bank at ground potential, and as the ratio of unswitched to switched capacity increases, the grounded case is more nearly approached. (Refer to cases VII and IX of Figure 10.)

Full-scale tests demonstrated that delta-connected or wye floating neutral capacitors up to 10,000 kva can be handled with standard breakers without creating the abnormal overvoltages indicated by the analysis. This appears to substantially satisfy present-day system requirements. Above these values a

Table V. Closing—Opening Tests in Which Capacitor Discharged Through Breaker on Initiation of Fault

For These Tests Capacitance = 857 Microfarads

No	X_L Ohm	E_G Volts	E_B Volts	I_1 RMS Before Closing	I_1* Peak on Closing (Measured)	I_1 Peak on Closing (Calculated)	I_1 Peak on Opening	I_2 Short-Circuit Peak on Closing (60 Cycles)	I_2 RMS Symmetrical Fault (60 Cycles)	Switching Angle Degrees	Natural Frequency (Cycles Per Second)	L_1 Millihenry Calculated From Test
Magne-Blast Breaker												
1	0.421	5,400	6,300	2,050	10,000	11,100	8,800	36,000	11,800	12	1,100	0.0244
2	0.421	5,400	6,300	2,050	42,000	47,000	9,700	25,000	11,700	62	1,100	0.0244
3	0.421	5,400	6,300	2,050	7,800	7,400	9,400	36,000 Figure 13b	11,800	8	1,100	0.0244
4	0.421	5,400	6,300	2,050	52,000	53,000	9,500	20,000 Figure 13a	11,800	86	1,100	0.0244
Oil-Blast Breaker												
5	0.421	5,400	6,300	2,050	38,000	44,000	8,450	27,000	10,900	48	1,220	0.020
6	0.329	5,400	6,040	1,950	8,000	8,350	8,500	45,000	14,400	9	1,160	0.022
7	0.329	5,400	6,040	1,950	37,000	44,200	8,750	32,000	14,500	56	1,160	0.022



* This peak current flows through breaker in addition to short-circuit current, but has disappeared with the arrival of peak short-circuit current.

The typical test results summarized in Table IV indicate the scope of these tests. Oil and Magne-blast breakers of the voltage class up to 15 kv and up to 250,000-kva interrupting capacity were tested. It is interesting to note that the Magne-blast breaker successfully interrupted 31,400 kva at 4,000 volts without disturbing overvoltage in spite of some restriking. This result is caused by the high series resistance present[4] when restriking occurs within the arc chute, see Figure 11a. This desirable characteristic of the Magne-blast type of breaker places it in a very favorable position when switching capacitive circuits. Figure 11 exhibits typical cathode-ray oscillograms of the voltages attending these interruptions.

The 15-kv, 250,000-interrupting-kva oil breaker was tested up to approximately 11,000 kva with results as tabulated. Figure 12 shows a typical recording of this series of tests when de-energizing the larger bank ratings.

Discussion of Results

The transient-analyzer approach allowed the circuit constants to be readily varied for determining generalized qualitative results, thus materially reducing the full-scale test requirements. Also, with complete control of the random phenomenon called "restriking," certain conclusions could be drawn with respect to the maximum possible overvoltages obtainable under the most pessimistic

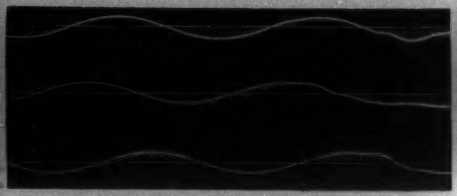


Figure 11a. Cathode-ray oscillogram showing the capacitor voltages to ground attending the interruption of a three-phase 6,500-kva bank with the Magne-blast air circuit breaker

See test 14 on Table IV

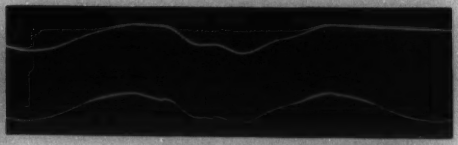


Figure 11b. Cathode-ray oscillogram of voltages to ground associated with the Magne-blast breaker opening a single-phase 3,300-kva 5,400-volt bank of capacitors

B—Capacitor volts
C—Bus volts

point is reached where restriking together with the attendant overvoltages becomes more probable, thus presenting a field for further development should the requirement greatly expand.

Capacitor Discharge During Short Circuit

When a short circuit occurs on the load side of a large capacitor bank, the capacitor discharges its energy into the fault—in some applications—along with the flow of short-circuit current. (See figure in Table V.) The question naturally arises regarding the extra duty, if any, required of the circuit breaker through which both of these currents flow. A study of the problem reveals that the most severe case of the above consideration concerns the closing of the breaker upon such a fault with immediate opening. The concern regarding this case is dispelled when it is realized that the maximum capacitor energy is "dumped" when the fault is initiated at the crest value of the system voltage. Under these conditions, the short-circuit current which flows is at its lowest value, namely the symmetrical value. In this case the highly damped capacitor discharge is practically over with the arrival of the first crest of normal-frequency short-circuit current. See Figure 13a.

If, on the other hand, the maximum short-circuit current is developed by initiating the fault at the zero point of the voltage wave, the capacitor charge is zero and hence contributes nothing. See Figure 13b.

Analysis shows that this latter case develops the maximum thermal and magnetic effects. Since this is a normal function of the breaker, it follows that the presence of the capacitor cannot add to the maximum closing duty of the breaker. It should be pointed out, in

Figure 12. Cathode-ray oscillogram showing the capacitor voltages to ground associated with the interruption of a three-phase 10,800-kva bank with an oil-blast circuit breaker

See test 6 on Table IV

Figure 13a. Fault initiated near the peak of generated voltage

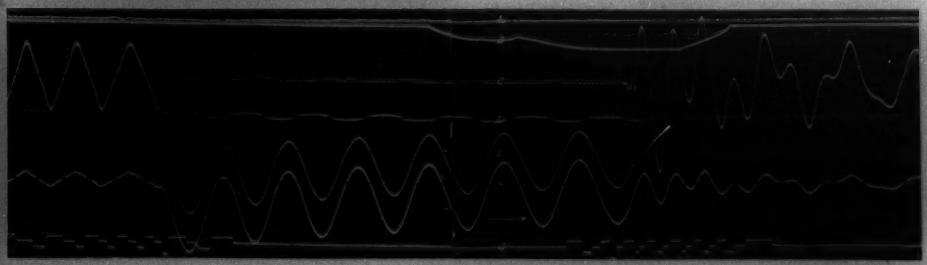
Maximum capacitor charge. Note the high capacitor discharge in the presence of approximately symmetrical fault conditions. See test 4, Table V

Figure 13 (left, below). Typical oscillograms showing the currents resulting when a circuit breaker closes upon and interrupts short circuit when a large capacitor bank is present on the bus

B—Trip-coil current
C—Capacitor current, I_1
E—Fault current, I_3
F—Line current, I_T
G—Breaker travel

Figure 13b. Fault initiated close to the minimum point of generated voltage

Minimum capacitor charge. Note the low capacitor contribution in the presence of the displaced short-circuit current. See test 3, Table V



addition to the above, that the presence of the shunt capacitor on the bus materially aids the circuit breaker in its duty by lowering the rate of rise of recovery voltage. This last deduction does not hold if the breaker is attempting to clear a *L-G* fault on a system that is susceptible to high arcing-fault voltages. Other[2] investigations indicate that on these systems the reduction of the ratio of capacitive zero-sequence reactance to the positive-sequence inductive reactance tends to give the more severe overvoltages if restrike occurs. These conditions however, are rare and can be eliminated by properly grounding the system. In order to determine breaker operation when performing this function, as well as an attempt to get higher inrush currents in the interests of completeness, tests were conducted in which short circuits were produced by closing breakers upon the fault and tripping with no time delay. Two oscillograms are shown demonstrating the above relationships. Figure 13a shows a fault initiated near the peak of generated voltage. Note that the high-frequency capacitor discharge is so short that, with the arrival of the first peak of the symmetrical short-circuit current, little of the capacitor discharge remains. Figure 13b shows a fault initiated near the zero of generated voltage, giving rise to a displaced fault. Note the insignificant contribution made by the capacitor. Table V shows a partial list of the tests made under these conditions. The above considerations show that the interrupting duty on a circuit breaker is not increased by the presence of a large shunt bank on the bus side. In no case did the breakers in this series of tests exhibit abnormal stress.

Appendix A. Sequential Energizing of a Three-Phase Ungrounded Wye Capacitor Bank—Inrush Current

Considering the circuit given by Figure 1a, switch *a* may be closed with no electrical effect. The maximum current in phase *ab* may be obtained by closing switch *b* at a time when the voltage across it, E_{ab}, is a maximum. Thus

$$i_a = -i_b = \frac{\sqrt{3}E\cos\omega t}{2\left(pL+\frac{1}{pc}\right)} = \frac{(1-a)E_g}{2Z(p)} \qquad (1)$$

where E = line-to-neutral generated voltage in phase *a*.

The voltage across the open switch *c* is

$$a^3E_a - \{E_a - i_aZ(p)\} \qquad (2)$$

which with equation 1 substituted is

$$E_a\left(a^3 - 1 + \frac{1}{2} - \frac{a}{2}\right) = \frac{3a^3}{2}E_a = -1.5E\sin\omega t \qquad (3)$$

It is interesting to note that the voltage across the last switch to close has no natural-frequency component, even though the current flowing in phases *b* and *c* at this time does have. This may be written

$$E_{ns_c} = -1.5E\sin(\omega t' + \theta) \qquad (4)$$

where

$\theta = \omega\,\Delta t$, and Δt is the time elapsed between the closing of switches *b* and *c*. Considering the effect of this voltage by itself,

$$i_c = \frac{-1.5E\sin(\omega t' + \theta)}{1.5Z(p)} \qquad (5)$$

At any time after Δt the total current in phases *a* and *b* is

$$I_{aT} = i_a - \frac{i_c}{2}$$

$$I_{bT} = -i_a - \frac{i_c}{2} \qquad (6)$$

Since I_{bT}, the total current in phase *b*, will be the largest, the operational expression for I_{bT} given by equation 6 will be solved.

$$-i_{bT} = \frac{\sqrt{3}E\cos\omega t}{2Z(p)} - \frac{E\sin(\omega t' + \theta)}{2Z(p)} \qquad (7)$$

The solution of this is

$$I_{bT} = I_0\left[\frac{\sqrt{3}}{2}\sin\omega t - \frac{\sqrt{3}}{2}\sqrt{X_C/X_L}\sin\omega_0 t + \frac{1}{2}\cos(\omega t' + \theta) - \frac{1}{2}\cos\theta\cos\omega_0 t' + \frac{1}{2}\sqrt{X_C/X_L}\sin\theta\sin\omega_0 t'\right] \qquad (8)$$

where

$I_0 = \dfrac{E}{Z}$ = normal capacitor current per phase

$X_C = \dfrac{1}{\omega C} \qquad X_L = \omega L$

$\omega_0 = \omega\sqrt{X_C/X_L}$ = natural frequency of the circuit

t terms are components of i_b, the current before switch *c* is closed

t' terms are components of $\dfrac{i_c}{2}$ the additional current after switch *c* is closed

Since the natural-frequency components of equation 8 have large coefficients by comparison with the forced frequency components, the latter may be neglected to simplify the task of determining the value of θ which will give the largest total component of current in phase *b*. The natural-frequency components are

$$I_{NF} = \sqrt{X_C/X_L}\left[-\frac{\sqrt{3}}{2}\sin\omega_0 t + \frac{1}{2}\sin\theta\left(\sin\omega_0 t\cos\frac{\omega_0}{\omega}\theta - \cos\omega_0 t\sin\frac{\omega_0}{\omega}\theta\right)\right] \qquad (9)$$

Putting $dI_{NF}/d\theta$ equal to zero permits the value of θ to be found which will give maximum I_{NF}. This will not be far from that which will put the two components of equation 9 inphase which, for a natural frequency of 5 is $\theta = 180/5 = 36$ degrees.

If $\theta = 36$, I_{NF} max $= \sqrt{X_C/X_L}$ 1.12

If $\theta = 40$, I_{NF} max $= \sqrt{X_C/X_L}$ 1.18

Adding 1.0 to $\sqrt{X_C/X_L}$ 1.18 to allow for fundamental frequency components of equation 9 gives

$I_{bT} = I_0(5.9 + 1.0) = 6.9I_0$

which is 15 per cent higher than I_{max} determined for simultaneous switching.

Appendix B. Capacitor De-Energizing Analysis; Capacitor Voltage upon Restrike

Case 2. Part of Bank Unswitched

Referring to Figure 8, just before restrike, at $t = 0$, the voltage existing across the switch $= -E(1 + \cos\omega t)$ neglecting the rise in voltage of point *a* due to *i*, flowing through *L*. The effect of closing the switch (restriking) may be obtained by applying this voltage to the operational impedance of the circuit, and the switch current is

$$i_2 = EC_2\frac{\omega_0^2}{\omega_1^2}\left[\frac{p(\omega_1^2 + p^2)}{(\omega_0^2 + p^2)} + \frac{p^2(\omega_1^2 + p^2)}{(\omega_0^2 + p^2)(\omega_2^2 + p^2)}\right] \qquad (10)$$

where

E = crest value of generated voltage

$\omega_1^2 = \dfrac{1}{LC_1}, \quad \omega_2^2 = \dfrac{1}{LC_2}, \quad \dfrac{1}{\omega_0^2} = \dfrac{1}{\omega_1^2} + \dfrac{1}{\omega_2^2}$

The change of voltage of capacitor C_2 due to the restrike is $\Delta e_{c_2} = i_2/pC_2$ for which the solution is

$$\Delta e_{c_2} = E\frac{\omega_0^2}{\omega_1^2}\left[\frac{\omega_1^2}{\omega_0^2} + -\frac{\omega_1^2}{\omega_0^2} + 1 + \frac{\omega_1^2 - \omega_0^2}{\omega^2 - \omega_0^2}\cos\omega_0 t + \frac{\omega^2 - \omega^2}{\omega_0^2 - \omega^2}\cos\omega t\right] \qquad (11)$$

If the natural frequency ω_0 is assumed very large compared with ω, then at $t = \pi/\omega_0$

$$\Delta e_{c_2} = 2E\left[\frac{C_1 + 2C_2}{C_1 + C_2}\right] \qquad (12)$$

and the capacitor voltage after restrike is

$$E_{c_2} = E - \Delta e_{c_2} = E\left[\frac{-C_1 - 3C_2}{C_1 + C_2}\right] \qquad (13)$$

For case II, where $C_1 = 0.2$ microfarad and $C_2 = 0.5$ microfarad, $E_{c_2} = (-17/7)E$. This value may be obtained by conservation of charge—the sum of the charges on the capacitors after restrike is the same as before, hence immediately after restrike

E of both capacitors $=$

$$\frac{Q_T}{C_T} = \frac{(-C_1 + C_2)E}{C_1 + C_2} = -\frac{3}{7}E$$

The equalized capacitor voltage must still change through $2C_2/C_1 + C_2E$ to arrive at the

Application of Vacuum-Tube Oscillators to Inductive and Dielectric Heating in Industry

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I. Introduction

THE knowledge that metals could be heated inductively and that nonconductors could be heated dielectrically dates from the earliest experiments with electricity. In the last few years inductive and dielectric losses, which have long been obstacles in the electrical industry, have been profitably employed in a new industrial tool powered by high-frequency motor-generator sets and vacuum-tube oscillators. Low-frequency inductive heating has been used in specialized melting applications for approximately 20 years and for some surface hardening work for the last ten years. However with the advent of the new equipment and knowledge of its use, it is no longer a highly restricted application but is ready to handle thousands of heating processes throughout the industry. Hence, it is felt that a short review of the theory of inductive and dielectric heating, together with a description of the vacuum-tube circuits used and some of their applications, would be of value at this time.

II. Classification of Equipment

Inductive heating can be roughly segregated by frequency into three classes. The first class covers applications to 1,000 cycles. It is almost entirely used for forging and melting steel and nonferrous metals either directly or indirectly (that is, by heating electrically conductive crucibles). Power requirements range from a few watts to thousands of kilowatts generated by motor-generator sets. It is being widely used to produce many of the specialized alloys demanded for war equipment.

The second class covers frequencies from 1,000 to 12,000 cycles almost entirely generated by rotating machines with power ratings of from 20 to 1,200 kw. The applications in this group cover practically all heating processes—surface hardening, forging, brazing, soldering, melting are all included. One to three thousand cycles are used for melting nonferrous alloys, for surface-hardening relatively large parts, and for some forging applications. The new 9,600-cycle generators are being used successfully for surface-hardening relatively small parts where the contours need not be too closely followed, and where the depth of case need not be too small. Widely used for brazing and soldering of other high-resistance metals, inductive heating is more difficult to apply to the heating of copper, brass, and other low-resistance alloys.

The third group for inductive heating covers all applications from 50,000 cycles to 1,000,000 cycles. Generation is almost entirely restricted to spark-gap and vacuum-tube oscillators. Spark-gap type of equipment can be built for frequencies from 50,000 cycles to 200,000 cycles and for power outputs up to 25 kw. Vacuum-tube equipment, while having no theoretical frequency or power limitation, is most economically applied at frequencies over 150,000 cycles and at power outputs up to 200 kw.

In the dielectric heating field the vacuum-tube oscillator is the only source capable of producing sufficient power at the frequencies necessary. From 1,000,000 to 30,000,000 cycles have been used at powers up to 200 kw.

III. Theories Involved

Before taking up some of the applications in greater detail, it might be well to review some of the fundamental theories involved. Any charge to be heated inductively can be thought of as a short-circuited secondary winding of a transformer, the primary being the heater coil. The currents produced in the charge heat it by resistive and hysteresis losses according to the well-established theory of eddy currents. The heat generated is confined to the surface of the parts by the skin-effect phenomena. The depth of penetration varies inversely with the square root of frequency, directly with the specific resistance of the material, and, in the case of magnetic materials, inversely with the permeability.

With nonmagnetic metals the heat is generated in this superficial volume throughout the heating cycle, varying only as the resistance of the metal changes

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Figure 1. Five-kilowatt power oscillator for high-frequency induction heating

system voltage, and in changing through the inductance it will overshoot this amount and become a negative maximum of

$$\left(\frac{2C_3}{C_1+C_3}+1\right)E=\frac{C_1+3C_3}{C_1+C_3}E$$

which agrees with equation 13.

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Figure 2. Fifteen-kilowatt power oscillator for high-frequency induction heating

with temperature—the core of the charge being heated largely by thermal conduction. Thus silver and copper are difficult to heat because of their low specific resistance and the resulting small depth of penetration. In magnetic materials the depth of the heated layer, which is very small due to the effect of the high permeability, increases rather abruptly at the temperature above which the material becomes nonmagnetic. Simultaneously, the power being absorbed in the original layer is reduced. Therefore steel with a high permeability and high specific resistance is readily heated in a thin surface layer while below the critical temperature, whereas above this temperature the power absorbed is less, and the depth of penetration considerably greater.

Because of these effects, the majority of steel parts can be readily surface-hardened at the intermediate frequencies by heating the surface inductively and quenching when the desired penetration has been achieved. Much higher frequencies are required for irregular parts where the contour must be followed closely, where coupling is difficult because of shape or small size, and where extreme localization of the heat is a necessity. To heat readily the low-resistance metals such as silver, copper, aluminum, and brass, the magnetic flux densities required at the intermediate frequencies are difficult to obtain, whereas the higher frequencies allow the use of more normal flux densities.

In dielectric heating the material to be heated is placed between two electrodes, and voltage applied at a frequency above 1,000,000 cycles. The whole forms a high-loss capacitor. The theory of dielectric losses is somewhat complex and is not yet thoroughly understood. However for most materials the heat developed is roughly proportional to the frequency and voltage applied and to the power factor of the dielectric. The entire mass is uniformly heated throughout, provided the electric field is uniform.

IV. Vacuum-Tube Circuits

The vacuum-tube oscillators used in the high-frequency field are of the simplest possible type. Radically departing from the usual radio construction practice, they are truly an industrial tool. Mechanically they are ruggedly built to withstand normal factory usage. Electrically they have been greatly simplified to provide the maximum reliability. The circuits most generally used are the Colpitts and the coupled-grid self-excited oscillator. In either of these circuits, the alternating supply voltage is stepped up by means of a power transformer to a voltage in the neighborhood of 7,500 volts to 15,000 volts and then rectified by a suitable bank of mercury vapor rectifier tubes. The direct current thus obtained supplies the oscillating circuit which consists primarily of a grid-controlled vacuum tube shunted across a parallel resonant circuit. The tube acts as a very rapidly operating switch. When this switch operates at the fundamental frequency of the parallel resonant circuit, it transmits power surges at this frequency by effectively short-circuiting the line once each cycle. Thus the voltage across the oscillation capacitor and inductance is alternately reduced and increased, setting up a circulating current in the resonant circuit.

To assure that the tubes operate at the desired frequency, their control grids are excited directly from the resonant circuit. This excitation voltage is obtained by several methods. In the Colpitts circuit (Figure 3) the excitation voltage is obtained by a direct tap on the oscillation capacitor, while in the coupled-grid circuit (Figure 4) it is developed in a coil inductively coupled to part of the oscillation inductance. All direct current is prevented from appearing in the resonant circuit by means of blocking capacitors. In both of these circuits the heater coil is usually in series with the parallel resonant circuit and forms part of the oscillation inductance. Since the frequency of operation is primarily determined by the constants of the resonant circuit, it will shift slightly as the inductance of the heater coil changes with load, thus always assuring operation at resonance and reducing fluctuations in the output current. For some applications requiring higher coil currents than are economically obtainable with a resonant circuit, an air-core transformer is used to step up the current.

V. Applications—Inductive Heating

This type of equipment can be applied to a great variety of heating problems. In the case of a small one-quarter-inch shaft the central portion was used as a bearing surface while the ends were riveted over to hold it in position. The overall length was approximately $1^1/_4$ inches. The problem was to harden the bearing surface while leaving the ends unaffected. Previously, this was achieved by copper-plating the ends and then casehardening the exposed parts by carburizing—a lengthy and expensive process. To apply induction hardening, a small coil was wound which was approximately the length of the desired hardened area. The part was centered in this coil, and the whole was immersed in water. Power at a frequency of 500,000 cycles was applied. As the steel heated up, a film of steam formed around that area, protecting it from the cooling action of the water.

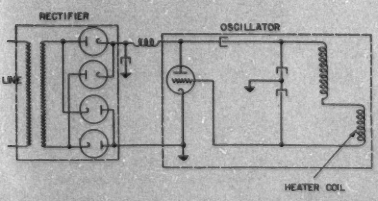
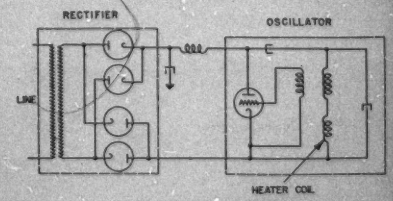


Figure 3 (left). Basic Colpitts oscillator circuit as used for induction heating

Figure 4 (right). Basic coupled-grid oscillator circuit as used for induction heating



But, when power was removed, this vapor envelope collapsed, allowing the water to rapidly quench the part. The entire cycle was complete in $3\frac{1}{2}$ seconds, and a satisfactorily hardened area obtained. Approximately four kilowatts output was used.

Curiously enough, in surface-hardening split pipe-threading dies an external coil can be used to harden the inside teeth. This is possible, because the induced currents must travel in a closed loop. Since there is no continuous external path around the circumference of a split die, the currents must travel completely around the inside of the die before returning to the outside surface. Thus such a die can be located inside a coil and, with proper heating and quenching cycles, can be hardened on both the inside and outside surfaces simultaneously, leaving a soft tough core.

In applying inductive heating to brazing, the usual procedure consists of assembling the fluxed parts using a preformed piece of brazing alloy between the parts. The advantages of the use of this method are speed, cleanliness, simplicity, and localization of heat. No experienced operators are necessary, and the method is admirably suited to automatic or semi-automatic operation.

In assembling the stator punchings of a small motor, the shell holding them had previously been spun over on either end. However, in using this method, the punchings had a tendency to work loose. To solve the problem, one end of the shell was spun over, the stator punchings assembled in position, and a thick washer placed over the end. A groove in the washer accommodated a ring of silver solder adjacent to the shell. The use of torch heating was impractical, because the heat conducted to the punchings tended to carbonize the insulating varnish. However, by using high-frequency induction, the heat could be so localized and the time interval used so short, that little heating of the punchings took place. Also, since the entire brazing operation could be performed while in a press, no loosening was encountered.

The manufacture of a small terminal

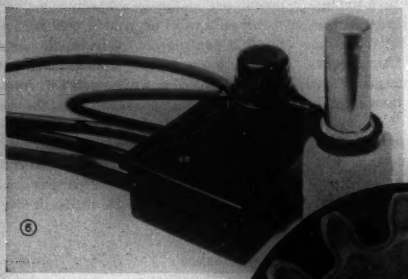


Figure 6. Brazing adapter on small assembly using air-core output transformer

Photo courtesy of Ajax Electrothermic Corporation

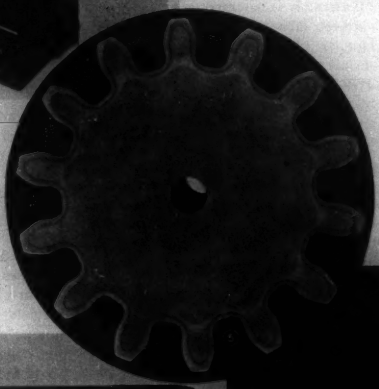


Figure 5 (right). Surface-hardened gear

Photo courtesy of The Ohio Crankshaft Company

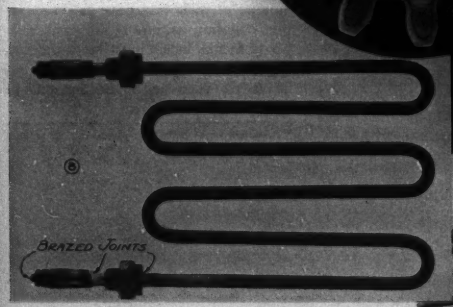


Figure 8. Nickel-silver-sheath Calrod unit resistor with Mycalex terminals and bushings inductively brazed

Figure 7. Terminal bushing assembly in which brazed joint and fused glass on rim were heated simultaneously

Figure 9. Focus inductor for specialized brazing showing output transformer with two-turn secondary winding

Photo courtesy of Ajax Electrothermic Corporation

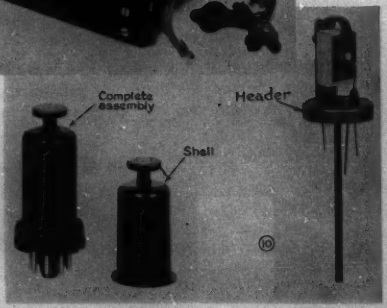


Figure 10. Metal-tube-type crystal unit

Shell soldered to header assembly by inductive heating

to be sealed in a glass bushing required two heating operations. First, the copper stud had to be silver-brazed to a nickel-steel alloy cup using a gas torch. Then, after spraying the rim of the cup with a suspension of finely divided glass in alcohol, the whole was fired in a muffle furnace to fuse the glass preparatory to sealing it into the insulator. These two operations are performed simultaneously, and a much more uniform product achieved by the induction heating method. The coil used is so proportioned that, as the proper temperature is reached for brazing at the joint, the flange is at the fusing temperature of the glass. The entire operation is complete in five seconds.

In the assembly of Calrod heating units the bushings and terminals are brazed in place. A great variety of metals must be heated since nickel-silver, copper, brass, and steel are all used for various applications. Also, the Mycalex insulating pieces must not be overheated or damage will result. Although the steel parts could be successfully heated using intermediate frequencies generated by rotating machines, high-frequency vacuum-tube equipment is used to obtain flexibility of operation throughout the range of materials used. Preformed silver solder rings are used. All operations being automatically controlled, there is no possibility of overheating or burning of the pieces. A further application of this machine has been the reclamation of short pieces of tubing previously regarded as scrap, since efforts to braze them together had been expensive and in many cases resulted in a weak joint. However, because of the uniformity of the brazed joint and the automatic operation made possible by inductive heat, these pieces are now being used successfully.

Because soft soldering is a low-temperature operation amenable to the use of resistance heating, only high-production items of an unusual nature have previously been attempted by induction methods. However, with the present-day enforced use of high-temperature soft solders, this application has been expanding rapidly.

In the manufacture of crystals as used in radio apparatus, one form of the crystal assembly is mounted on a header and enclosed in a shell very similar to the familiar small metal radio tube. The shell is soft-soldered to the base or header. This operation was performed in the past by pretinning the flange on the shell and the rim of the base and making the final joint in a ring burner, adding such solder as was necessary. However, the products of combustion of the gas used sometimes condensed on the crystal surface and seriously affected its operation. Also, the heat transmitted through the supporting bracket occasionally cracked the crystal. By heating inductively, the heat is entirely confined to the rim, and the operation considerably speeded up.

VI. Applications—Dielectric Heating

Dielectric heating of nonconducting materials is the newest application in the field and shows great promise of rapid development. Already one large unit has been placed in operation curing the glue in plywood with promise of many other such installations.* Several unsuccessful trials have been made to cure rubber by this method, but the applications to plastics, ceramics, and insulating compounds are progressing rapidly.

Not only will this type of heat reduce the time of curing of many plastic parts (a reduction in the case of thick laminated plastic insulating compounds of from hours to minutes), but it will allow the use of some types of plastics in forms previously impossible because of the difficulty of properly curing the material. Within the next two years it is expected that considerable progress will be made in this direction.

VII. Closure

A word of caution regarding the application of this type of equipment. The rotating machine and the high-frequency oscillator supplement but cannot replace each other. It is neither economically nor theoretically sound to attempt to heat large regularly shaped steel parts by use of oscillators, nor is it wise to use rotating machines of high power to heat a small irregular part where a low power oscillator could be applied. There is little overlapping of their respective fields of application, but, because of the great number of factors which must be considered, no broad definitions of their fields can be made. Thus each application must be judged on its own merit.

* Installed at M & M Woodworking Company, Plylock division, Albany, Oregon by the Thermex division of the Girdler Corporation.